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The Great Escape: Discovery of a nearby 1700 km/s star ejected from the Milky Way by Sgr A* 

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ABSTRACT

We present the serendipitous discovery of the fastest Main Sequence hyper-velocity star (HVS) by the Southern Stellar Stream Spectroscopic Survey (S5). The star S5-HVS1 is a ~ 2.35 M⊙ A-type star located at a distance of ~ 9 kpc from the Sun and has a heliocentric radial velocity of 1017 ± 2.7 km s⁻¹ without any signature of velocity variability. The current 3-D velocity of the star in the Galactic frame is 1755 ± 50 km s⁻¹. When integrated backwards in time, the orbit of the star points unambiguously to the Galactic Centre, implying that S5-HVS1 was kicked away from Sgr A* with a velocity of ~ 1800 km s⁻¹ and travelled for 4.8 Myr to its current location. This is so far the only HVS confidently associated with the Galactic Centre. S5-HVS1 is also the first hyper-velocity star to provide constraints on the geometry and kinematics of the Galaxy, such as the Solar motion V_{x,y,z} = 246.1 ± 5.3 km s⁻¹ or position R₀ = 8.12 ± 0.23 kpc. The ejection trajectory and transit time of S5-HVS1 coincide with the orbital plane and age of the annular disk of young stars at the Galactic centre, and thus may be linked to its formation. With the S5-HVS1 ejection velocity being almost twice the velocity of other hyper-velocity stars previously associated with the Galactic Centre, we question whether they have been generated by the same mechanism or whether the ejection velocity distribution has been constant over time.

Key words: stars: kinematics and dynamics – Galaxy: centre – Galaxy: fundamental parameters

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1 INTRODUCTION

Throughout the last 100 years of studying our Galaxy, there was always a prominent niche in identifying fast moving stars on the sky or in 3-D. One of the first studies of high-velocity stars was the PhD thesis by Oort (1926) who put a boundary between high velocity and low velocity stars at 63 km s$^{-1}$. Initially, the searches for fast moving stars were focused on using the proper motions (van Maanen 1917; Luyten 1979) because these were easier to obtain in larger numbers than radial velocities. Due to the fact that the tangential velocities are distance dependent, these searches provided us with some of the first large samples of nearby and Milky Way (MW) halo stars (Barnard 1916; Eggen & Greenstein 1967; Eggen 1983).

When larger numbers of radial velocities began to be analysed in the 1950s–1960s (Kennedy & Przybyski 1963) the term “high velocity star” was used to refer to the stars with space velocities of $\gtrsim 100$ km s$^{-1}$ (Keenan & Keller 1953), where those stars were mostly MW stellar halo stars (Eggen et al. 1962). Around the same time, another type of high velocity object emerged – the runaway OB stars (Blauw & Morgan 1954). These stars did not have extreme space velocities, but instead were offset from the expected velocity of the disk by 100–200 km s$^{-1}$. Some stars were later found in the MW halo (Greenstein & Sargent 1974) with velocities up to 200 km s$^{-1}$.

The mechanism proposed for the formation of such high velocity stars involves either a supernovae explosion in a binary (Blauw 1961) or ejection due to encounters in clusters (Poveda et al. 1967).

For a while these pathways seemed to be the most promising for creating fast moving stars in the Galaxy with velocities potentially up to the escape speed. However Hills (1988) proposed an entirely new mechanism of creating fast moving stars with velocities of 1000 km s$^{-1}$ and above (labelled hyper-velocity stars, HVS) by interaction of a stellar binary with a super-massive Black Hole (SMBH) in the centres of galaxies. This mechanism was almost forgotten until the early 2000s, when Yu & Tremaine (2003) analysed the ejection mechanism from single and binary SMBHs and Brown et al. (2005) identified a star in the Milky Way halo at a distance of 40 – 70 kpc with a total velocity of $\lesssim 700$ km s$^{-1}$, well above the escape velocity at such a distance. This discovery spurred a renewed interest in hyper-velocity stars (Edelmann et al. 2005; Hirsch et al. 2005; Heber et al. 2008; Przybilla et al. 2008) and led to dedicated searches, resulting in multiple new HVS (Zheng et al. 2014; Huang et al. 2017; Irgang et al. 2019) and candidate HVS (see Brown 2015, for a detailed overview and more references).

The most recent part of the story is the arrival of Gaia data (Gaia Collaboration et al. 2016), in particular Data Release 2 (Gaia Collaboration et al. 2018) that provided high accuracy proper motions, and thus enabled new discoveries (Shen et al. 2018), potential discoveries (Marchetti et al. 2018; Hattori et al. 2018a; Bromley et al. 2018; Boubert et al. 2019) as well as detailed studies of the HVS origins (Boubert et al. 2018; Brown et al. 2018; Irgang et al. 2018; Erkal et al. 2019). One of the key conclusions from these studies is that despite the large number of HVS candidates, only a handful of these appear to be actually unbound from the Galaxy and consistent with ejection from the Galactic Centre (GC).

Whilst the extreme speed of several of the HVS in the outer halo is seemingly unexplainable without the Hills mechanism, the uncertainties on their distances and proper motions are such that they cannot be tracked back precisely to the GC. The most convincing association to date is the star J01020100-7122208, identified by Massey et al. (2018) as a bound runaway star that in a particular choice of potential tracked back to the Galactic Centre; however, the low 3-D velocity of 296 km s$^{-1}$ does not preclude a more standard origin. There is not yet an example of an HVS that unequivocally tracks back to the GC, and thus no smoking gun for a GC Hills mechanism ejection. The power of HVS as probes of the Galactic potential (Gnedin et al. 2005) and the orbit of the Sun (Hattori et al. 2018b) is contingent on an unambiguous GC origin, and thus it is of paramount importance that such a smoking gun is found.

In this paper we present the discovery of a new nearby unbound HVS that can be unambiguously traced back to the Galactic Centre. The star is named S5-HVS1 as it was found in the Southern Stellar Stream Spectroscopic Survey ($S^5$, Li et al. 2019).

The structure of the paper is as follows. In Section 2 we briefly introduce the $S^5$ survey data that was used to identify the S5-HVS1 star and the search for HVS stars in $S^5$ data. In Section 3 we look at the spectroscopic and photometric properties of S5-HVS1. In Section 4 we analyse the kinematics of the star and its possible origin in the Galaxy. In Section 5 we focus on the Galactic Centre as a source of S5-HVS1 as well as inferences we can make on the Galactic potential, distance and velocity of the Sun with respect to the Galactic Centre. We discuss S5-HVS1 in more detail in Section 6 by comparing it to other HVS, as well as examining HVS ejection mechanisms. Our conclusions are given in Section 7.

2 DATA

The $S^5$ project is a survey devoted to the observation of stellar streams in the Southern Hemisphere (Li et al. 2019). The survey is being conducted on the 3.9 m Anglo-Australian Telescope (AAT) with the Two-degree Field (2dF) fibre positioner feeding the AAOmega dual arm spectrograph (Lewis et al. 2002; Sharp et al. 2006). $S^5$ uses low (5800V, R = 1300) and high (17000D, R = 10000) resolution gratings in the blue and red wavelength ranges respectively, covering the Balmer break region ($3800 < \lambda < 5800$ Å) in the blue and IR Calcium triplet (8400 < $\lambda$ < 8800 Å) in the red. The survey is ongoing, but by early 2019 it had observed 110 fields spread across $\sim 330$ square degrees and $\sim 40000$ targets. For details we refer the reader to the Li et al. (2019) paper, while providing here only the key aspects of the survey.

$S^5$ is primarily targeting stellar stream candidate members, selected based on photometric information from the Dark Energy Survey (DES) DR1 (Abbott et al. 2018) and proper motion and parallax information from Gaia DR2 (Gaia Collaboration et al. 2016, 2018). To fill all the 392 fibres of the spectrograph other target classes are observed, including low-redshift galaxy candidates, white dwarfs (WDs), and metal-poor stars, etc. The survey specifically targets blue stars that could be either Blue Horizontal Branch (BHB) stars, Blue Stragglers (BS) or RR Lyrae stars at a large range of distances. The selection used by $S^5$ for the BHB/BS stars is $-0.4 < (g − r) < 0.1$ and parallax $< 3 \sigma_{\text{parallax}} + 0.2$, combined with the star-galaxy separation criteria using astrometric excess noise quantities from Gaia (Lindegren et al. 2018; Koposov et al. 2017) and wavg_spread_model quantities from DES (see Eq. 1-3 in Li et al. 2019). At the time of writing the $S^5$ catalogue contains spectra of $\sim 3500$ blue faint objects. While many of them end up being quasars (see Li et al. 2019), $\sim 2200$ of them are likely BHB/BS/WD stars.

The data processing of the $S^5$ data includes standard data reduction steps by the AAT pipeline, followed by spectral modelling.
by the *rvspecfit*\(^1\) software in order to determine the radial velocities and stellar atmospheric parameters.

### 2.1 HVS star search

While identifying hyper-velocity stars was not a main goal of the \(S^5\) survey, the catalogue of radial velocities (RVs) and spectral fits was inspected for stars with velocities larger than 800 km s\(^{-1}\). The majority of objects with such high RVs were spurious measurements caused by either sky subtraction residuals and/or low signal-to-noise spectra, however the search identified a single bright (\(\sim 343\)) star with the Gaia DR2 source id 6513109241989477504 and \((\alpha, \delta) = (343.715345\(^\circ\), -51.195607\(^\circ\))\), located in the field of the Jhelum stellar stream, a new stellar stream found in the DES (Shipp et al. 2018). This star had a confident radial velocity measurement of \(\sim 1020\) km s\(^{-1}\), making it one of the fastest moving stars known in the Galaxy. The radial velocity of this star alone, irrespective of the distance, is enough to make the star unbound to the Galaxy (see e.g. Kafle et al. 2014). We label this star S5-HVS1\(^2\). In the next sections we focus on the detailed measurements of S5-HVS1 properties: spectroscopic, photometric and kinematic.

### 3 S5-HVS1 PROPERTIES

In this section we discuss the key spectroscopic properties of S5-HVS1 as determined from AAT data, as well as all available photometric data. The summary of these measurements is presented in Table 1.

#### 3.1 Spectroscopy

The star S5-HVS1 was observed for the first time at the AAT as part of regular \(S^5\) observations of the Jhelum stellar stream with the 580V and 1700D gratings on 2018 August 1. The total exposure time was 2 hours split into three individual exposures. The combined, reduced spectra for S5-HVS1 are shown in Figure 1. Based on the spectra, the star appears to be a hot A-type star with prominent broad Balmer and Paschen series and several metal lines like Ca II \(\lambda\)'s 4227, 3968, 3933 (4481\(\lambda\)) in the blue and Calcium triplet in the red.

Although the stellar spectra of S5-HVS1 in both the blue and red arms were analysed as part of the regular \(S^5\) processing (see Li et al. 2019), the analysis treated the blue and red arms separately. For this paper, however, we analyse the blue and red parts of spectra simultaneously in order to better constrain stellar atmospheric parameters. The fitting of stellar spectra is analogous to the procedure described in the \(S^5\) overview paper and uses the *rvspecfit*, but instead of considering the likelihood function of the red arm or blue arm data separately, we combine them. Specifically the model for the stellar spectrum uses a combination of global Radial Basis Function interpolation and local linear N-d interpolation of spectra from the PHOENIX-2.0 library (Husser et al. 2013) together with a multiplicative polynomial to deal with the fact that the observed spectra were not flux calibrated (see Koposov et al. 2011).

\(^1\) [http://github.com/segasai/rvspecfit](http://github.com/segasai/rvspecfit)

\(^2\) S5-HVS1 was previously photometrically identified as a candidate field BHB star by Christlieb et al. (2005) and given the designation HE 2251–5127.

### Table 1. The measured parameters of the hyper-velocity star S5-HVS1.

The top part of the Table refers to the measurements from previous surveys, while the bottom one summarises the measurements presented in the paper. HRV is the heliocentric radial velocity, \(\mu_{\alpha}\) _hel_, \(\mu_{\delta}\) _hel_ are heliocentric distance constraints without and with the Galactocentric origin assumption respectively. \(V_{\text{GSR}}\), \(V_{\text{GSR,GC}}\) are the inferred Galactic standard of rest (GSR) velocities of S5-HVS1 determined without and with the Galactocentric origin assumption respectively. \(V_{\text{GC}}\) is the expected ejection speed from the Galactic Centre, \(\mu_{\alpha,\text{pred}}\cos\delta, \mu_{\delta,\text{pred}}\) are the predicted proper motions of S5-HVS1 based on the Galactocentric origin.

| Parameter | Value | unit |
|-----------|-------|------|
| Gaia RA | 343.715345 | deg |
| Gaia Dec | -51.195607 | deg |
| Gaia DR2 source id | 6513109241989477504 | |
| Gaia \(\mu_{\alpha}\) cos \(\delta\) | 35.328 ± 0.084 | mas yr\(^{-1}\) |
| Gaia \(\mu_{\delta}\) | 0.587 ± 0.125 | mas yr\(^{-1}\) |
| Gaia Parallax | -0.042 ± 0.091 | mas |
| \(E(B-V)\) – \(V_{\text{hel}}\) | 0.00721 | |
| Gaia \(G\) | 16.0211 | mag |
| DES \(g, r, i, z\) | 15.90, 16.16, 16.40, 16.53 | mag |
| \(G_{\text{BP}} – G_{\text{RP}}\) | -0.0082 ± 0.0066 | mag |
| HRV | 1017.0 ± 2.7 | km s\(^{-1}\) |
| \(T_{\alpha}\) | 9630 ± 110 | K |
| log \(g\) | 4.23 ± 0.03 | dex |
| [Fe/H] | 0.29 ± 0.08 | dex |
| \(\log_{10} D_{\text{hel}/1kpc}\) | 0.936 ± 0.015 | |
| \(V_{\text{GSR}}\) | 1755±55 | km s\(^{-1}\) |
| \(V_{\text{GSR,GC}}\) | 1717.4 ± 3.5 | km s\(^{-1}\) |
| \(V_{\text{GC}}\) | 1798.6 ± 3.1 | km s\(^{-1}\) |
| \(D_{\text{hel}}\) | 8884 ± 11 | pc |
| \(\mu_{\alpha,\text{pred}}\cos\delta\) | 35.333 ± 0.080 | mas yr\(^{-1}\) |
| \(\mu_{\delta,\text{pred}}\) | 0.617 ± 0.011 | mas yr\(^{-1}\) |

\[ T(\lambda) = \int \frac{1}{c} T_{\lambda} \log g, T_{\text{eff}}, \text{[Fe/H]} \]

Here \(T\) is the wavelength, the \(T(\lambda, \log g, T_{\text{eff}}, \text{[Fe/H]}\) is the interpolated stellar template, \(V\) is the radial velocity, \(a_i\) are fitted coefficients and \(n_p\) is the degree of the multiplicative polynomial used to correct for continuum normalisation\(^3\). The parameters of the model for the star were then sampled using the parallel tempering Ensemble sampling algorithm (Goodman & Weare 2010; Foreman-Mackey et al. 2013) to determine uncertainties. We adopted non-informative uniform priors on all parameters (i.e. contrary to Li et al. 2019, we did not use the \(T_{\text{eff}}\) prior based on the colour of the star).

The red curve in Figure 1 shows the best-fit spectral model corresponding to the maximum likelihood set of parameters. The stellar atmospheric parameters are effective temperature \(T_{\text{eff}} = 9630 ± 110\) K, surface gravity \(\log g = 4.23 ± 0.02\), and high stellar metallicity \([\text{Fe/H}] = 0.29 ± 0.08\). We note though that the posterior is bi-modal with two modes at \(T_{\text{eff}}\) ([Fe/H]) ~ (9500K, 0.25) and (9700K, 0.4). This is likely caused by the limitations of the adopted

\(^3\) Since the blue arm part of the spectra has a much larger wavelength calibration uncertainty (see Li et al. 2019), when we fit for stellar atmospheric parameters we allowed for a small RV offset between blue and red arms.
stellar atmosphere grid and interpolation procedure, as the resolution of the PHOENIX grid is 0.5 dex in \( \log g \) and [Fe/H] and \( \sim 200 - 500 \) K in \( T_{\text{eff}} \). Because of this, the uncertainties on the stellar atmospheric parameters should be mostly systematic. Despite that, the measured surface gravity of S5-HVS1 strongly suggests that the star is a Main sequence A-type star as opposed to a Blue Horizontal Branch star with \( \log g \lesssim 3.5 \).

While we determined the atmospheric parameters for S5-HVS1 from simultaneous fitting of the red and blue spectra separately from main \( S^3 \) data processing, the radial velocity measurement for the S5-HVS1 that we will use comes from the main \( S^5 \) catalogue. The RVs in the catalogue rely only on the red arm of the spectra, as its wavelength calibration and stability are much better controlled due to a higher spectral resolution and the presence of large number of skylines in the science spectra. As discussed in detail in Li et al. (2019), the radial velocities and their uncertainties measured in \( S^5 \) have been validated with both repeated observations and observations of Gaia RVS and APOGEE stars. The uncertainties on the radial velocities also take into account the systematic error floor in our observations of \( \sim 0.6 \) km s\(^{-1}\). The heliocentric radial velocity measured for S5-HVS1 by \( S^5 \) is \( 1017.0 \pm 2.7 \) km s\(^{-1}\). The blue arm spectrum provides an independent velocity measurement with a similar value albeit with much larger error-bar 1017 \( \pm 23 \) km s\(^{-1}\).

### 3.2 Radial velocity variability

The radial velocity of S5-HVS1 is extreme and thus we must consider the possibility that it is due to binary motion. To check this hypothesis, we re-observed the star almost 8 months after the first observation. The first repeated observation was done on 2019 April 6 (MJD 58579.78; i.e., 240 days after the first observation) again using AAT 2dF spectrograph in the same configuration as in the \( S^5 \) survey. We ensured that S5-HVS1 was assigned to a different fibre plate and fibre from our 2018 observation to rule out any possible fibre-specific effects. The observations were performed in twilight and had an exposure time of only 2 \( \times \) 900s and therefore were of lower S/N than standard \( S^5 \) data\(^5\). Consequently the red (1700D) spectrum was not usable, but fortunately the 580V blue spectrum had S/N \( \sim 3 \) and we were able to measure a velocity \( V = 1017 \pm 24 \) km s\(^{-1}\) which is consistent within uncertainties with the original measurement.

We also carried out a further re-observation of S5-HVS1 on 2019 April 26 (MJD 58599.78) using the WiFeS integral field spectrograph (Dopita et al. 2010) on the ANU 2.3m telescope at Siding Spring Observatory. The instrumental setup employed the B3000 grating that gives resolution \( R \sim 3000 \) and wavelength coverage of 3500–5600Å. Two 900s exposures were obtained and the combined reduced spectrum yielded a heliocentric velocity of 1005 \( \pm 15 \) km s\(^{-1}\), which is entirely consistent with the other observations. In addition, model atmosphere spectral fits to the WiFeS flux-calibrated spectrum yielded an effective temperature of approximately 10,000 K, and more importantly, a surface gravity \( \log g \) of 4.5, confirming the main sequence star nature of S5-HVS1.

From these additional observations spread over a few months, we can convincingly rule out a binary origin of the high velocity of S5-HVS1, because high binary orbital velocities \( \gtrsim 100 \) km s\(^{-1}\) are only expected in binaries with high masses and short periods. It is still possible that S5-HVS1 is part of a long-period binary with a small orbital velocity that is undetectable in a period of \( \sim 1 \) year, but

\(^4\) We remark that formally the star lies on the BHB side of the \( \log g, T_{\text{eff}} \) distribution shown on Figure 11 of Li et al. (2019). However the analysis presented in Li et al. (2019) relied only on 1700D data as opposed to combination of 580V and 1700D data that we use here, and is therefore somewhat on different scale.

\(^5\) On 2019 April 6, this star was above airmass \( \sim 2 \) for only 10 min before astronomical twilight.
Spectral energy distribution (SED) of S5-HVS1 from GALEX, Gaia, SkyMapper, DES, 2MASS and WISE photometry. The blue curve is the black-body spectrum with temperature of 10000 K. The red line shows the SED from the best-fit MIST isochrone model. The magnitudes in the data and model were not extinction corrected.

this orbital motion would be negligible compared to the observed RV. Therefore most of the observed radial velocity must be caused by the motion through the Galaxy.

3.3 Photometry

S5-HVS1 was targeted by SS as a blue star with −0.4 < g − r < 0.1, which makes it a possible BHB or BS. In this Section we assess the photometric properties of S5-HVS1 by collecting its photometry across multiple wavelengths and fitting these data with an isochrone model.

As S5-HVS1 is quite bright, Gaia G ∼ 16, it is detected in a large number of different surveys. Here we take the data from DES DR1 (Abbott et al. 2018), 2MASS (Skrutskie et al. 2006), AllWISE (Wright et al. 2010), SkyMapper DR1.1 (Wolf et al. 2018), GALEX (Martin et al. 2005; Bianchi et al. 2017) and Gaia DR2 (Brown et al. 2018; Evans et al. 2018). Figure 2 shows all S5-HVS1 magnitudes (converted when needed from Vega to AB magnitude system) as a function of the effective wavelength of the corresponding filter with standard errors. The SED is clearly indicative of a hot star with temperature ∼ 10000 K. The red line shows the photometry from the best fit isochrone model in the observed filters that we describe below. The blue line shows a black body spectrum with a temperature of 10000 K.

To model the photometry of S5-HVS1 we use the MIST isochrones (Dotter 2016; Choi et al. 2016, version 1.2) and to interpolate between isochrones we use the isochrones software (Morton 2015, version 2.0.1)6. The data that we model are the observed magnitudes mi where i corresponds to the i-th band. The isochrones provide us with absolute magnitudes, surface gravities and effective temperatures as a function of stellar age, mass, metallicity and band-pass M(age, M, [Fe/H], i). Assuming Gaussian uncertainties of observed magnitudes, our model is

\[
m_i = m_i^0 + 5 \log_{10} D_{hel} - 5 + k_i E(B - V), \sqrt{\sigma_i^2 + \sigma_{sys}^2},
\]

where \( \sigma_i^2 \) is the uncertainty on the magnitude measurement in band i, \( \sigma_{sys} \) is an additional (systematic) scatter around the model, \( D_{hel} \) is the heliocentric distance to the star, and \( k_i \) is the extinction coefficient7 in the filter i. On top of the purely photometric model described in Eq. 1 (we label it Model P), we also consider a model (labelled Model SP) where we complement Eq. 1 with the constraints on log g, \( T_{eff} \) and [Fe/H] from the spectroscopic analysis (see Section 3.1), assuming they are normally distributed (i.e. we multiply the likelihood by a Gaussian term for log g, \( T_{eff} \) and [Fe/H]).

We adopt generically uninformative priors for the parameters: uniform distribution on (linear) age ∼ U(100, 12 × 1010), Salpeter IMF prior for the stellar mass from \( M \sim 0.1 \, M_\odot \) to \( M \sim 5 \, M_\odot \), uniform prior on metallicity [Fe/H] ∼ U(−4, 0.5), and a uniform prior on distance modulus \( 5 \log_{10} D_{hel} - 5 \sim U(10, 20) \) corresponding to a 1/D2 spatial density prior from 1 kpc to 100 kpc. For the extinction, we adopt a prior around the Schlegel et al. (1998) value \( E(B − V) \sim U(0.3E_{34SP}, 3E_{34SP}) \). The posterior of the model is sampled using the nested sampling MultiNest algorithm (Feroz & Hobson 2008; Buchner et al. 2014).

The posterior of the model parameters is shown in Figure 3; blue contours and curves for Model P and green for Model SP. Focusing on the Model P first, we notice that as expected from photometric only data there are considerable degeneracies between mass, age, metallicity and distance of the star. The summary of parameters for Model P is provided in Table 2. The age of the star is consistent with a broad range of ages up to 500 Myr. The mass of the star is inferred to be 1.9 ± 0.25 M_\odot. The distance to the star is constrained to be \( 0.19 \pm 0.03 \, M_\odot \) from the Sun. We notice that this distance corresponds to a parallax of \( \pi_{phot} \sim 0.14 \, mas \) which is consistent within 2 sigma with the negative Gaia parallax measurement \( \pi_{Gaia} = -0.04 \pm 0.01 \, mas \) that was not used in the fit. The systematic error for the photometry is determined by the model to be \( \sigma_{sys} = 0.04 \pm 0.01 \) showing that there is no large discrepancy between isochrone models and data.

The match between the data and the isochrone model across the

\[ (1) \]

Table 2. The parameters measured from fitting MIST isochrones to the S5-HVS1 SED (Model P) and by combining SED constraints with spectroscopic constraints (Model SP).

| Parameter       | Value          | Value          | unit |
|-----------------|----------------|----------------|------|
| Mass            | 1.90 ± 0.25    | 2.35 ± 0.06    | \( M_\odot \) |
| log_{10} age    | 8.36 ± 0.32    | 7.72 ± 0.25    | dex  |
| [Fe/H]          | −0.46 ± 0.2    | −0.33          | dex  |
| m-M             | 14.2 ± 0.37    | 14.68 ± 0.07   | mag  |
| \( \sigma_{sys} \) | 0.04 ± 0.01    | 0.03 ± 0.01    | mag  |

6 For Gaia G⋆BP, G⋆RP magnitudes we use the band-passes defined by Weiler (2018).

7 Taken from http://www.mso.anu.edu.au/~brad/filters.html
Figure 3. The posterior on stellar parameters of S5-HVS1 from fitting MIST isochrones to the SED data only (blue) and the SED data combined with the prior on stellar atmospheric parameters from spectroscopic analysis (green). The red points with error-bars are showing the best-fit measurement of stellar atmospheric parameters from the analysis of the AAT spectra using rvspecfit. The pink lines on several panels identify the heliocentric distance to the star that is consistent with the Galactocentric origin (see Section 5). The contour levels in the 2-D marginal distributions correspond to the 68%, 95% and 99.7% of posterior volumes.

wavelengths is well demonstrated by Figure 2. Red points with error-bars shown on multiple panels of Figure 3 mark the parameter values measured from spectroscopic analysis of S5-HVS1 (Section 3.1). The measurements from photometric data only are broadly consistent with the spectroscopic analysis, as the error-bars overlap with the high probability parts of the posterior. Although there is possibly a small discrepancy in temperature of $\sim 200$ K and/or $[\text{Fe/H}]$ of $\sim 0.2$ dex between purely spectroscopic and photometric measurements, we believe this level of disagreement is well within the systematic errors of our spectroscopic and isochrone modelling.

Since the photometric and spectroscopic analyses are consistent, we also show in the Figure the posterior from the combination of the spectroscopic and photometric analyses (Model SP) as green contours. As expected, the combination of the datasets shrinks the posteriors considerably, i.e. the combined mass estimate is $2.35 \pm 0.06 M_\odot$ and distance estimate is $\log D_{\text{hel}} = 0.936 \pm 0.015$. The posterior estimates for these and other parameters from the Model SP are also provided in Table 2. Throughout the paper we use both the photometric and photometric+spectroscopic sets of estimates, where we will interpret the photometric-only constraints as
being more conservative. As we will discuss in the next section, the kinematics of S5-HVS1 are consistent with ejection from the Galactic Centre if the star has a very specific heliocentric distance of \( \sim 8.8 \) kpc. Pink lines on Figure 3 show the heliocentric distance to the star that is consistent with ejection from the GC (see Section 5), and we remark that this distance agrees perfectly with both the photometric and spectro-photometric analyses.

While the isochrone modelling performed so far did include the horizontal branch phase, the posterior on the stellar parameters indicates that the photometry of S5-HVS1 is inconsistent with it being a Blue Horizontal Branch (BHB) star. However, it is still worth specifically addressing the possibility that S5-HVS1 is a BHB, because this is quite feasible given the star’s colour of \( g - r \sim -0.27 \) (most BHB stars have colours of \(-0.3 \lesssim g - r \lesssim 0\), Yanny et al. 2000). We therefore perform an independent check to assess the BHB hypothesis by looking at measurements of \( g - r \) and \( i - z \) colours. This colour combination is known to be sensitive to the surface gravity of stars due to the Paschen break contribution to the \( g \)-band, and therefore allows us to separate BHB from BS/MS stars (see e.g., Vickers et al. 2012; Belokurov & Koposov 2016). With colours of \( (g - r) = -0.27 \) and \( (i - z) = -0.13 \), S5-HVS1 sits significantly below the line separating the BHB from BS/MS (see right panel of figure 11 and eq. 5 of Li et al. 2019) further confirming that S5-HVS1 is a Main Sequence star. Additionally, when looking at the distribution of surface gravities and effective temperatures (left panel of figure 11 of Li et al. 2019) S5-HVS1 lies on the BS side of the distribution. Thus for future analysis, unless specified otherwise, we will adopt the Main Sequence based distance constraints determined in this Section.

## 4 KINEMATICS OF S5-HVS1

The extreme radial velocity of S5-HVS1 as measured from the observed spectra makes it one of the fastest stars known in the Galaxy and thus warrants a detailed investigation of its orbit and origin. Summarizing the phase-space information available for S5-HVS1, the position of the star on the sky is known very precisely, as is the radial velocity. The proper motion of the star is available in the Gaia DR2 catalogue and, because of the star’s brightness \( G \sim 16 \), it is also very precise \( (\mu_g \cos \delta, \mu_\delta) = (35.328 \pm 0.084, 0.587 \pm 0.125) \) mas yr\(^{-1}\). The only phase space parameter that is poorly constrained is the heliocentric distance, as discussed in Section 3.3. This is why we expect that most of the orbital inferences for S5-HVS1 should show a 1-D degeneracy corresponding to a range of possible heliocentric distances. Even with the more conservative (Model P) distance estimates, it is clear from combining the radial velocity and proper motions that the S5-HVS1 velocity in the Galactic frame is in excess of \( \sim 1200 \) km s\(^{-1}\). \( V_{\text{3D}} = 1470^{+166}_{-147} \) km s\(^{-1}\).

As a first step in modelling the orbit of S5-HVS1, we perform a backward integration of its current phase space coordinates to infer a possible ejection site of the star. Since the current total velocity of S5-HVS1 is at least 1200 km s\(^{-1}\), one of the key questions we are interested in is whether the star has been ejected from the Galactic Centre, the MW disk, or some other system such as a globular cluster or satellite galaxy. While some fast moving stars have been associated with other galaxies like the Large Magellanic Cloud (Edelmann et al. 2005; Gualandris & Portegies Zwart 2007; Boubert & Evans 2016; Boubert et al. 2017; Irigang et al. 2018; Erkal et al. 2019), in this paper we will focus only on ejection from the MW disk and the Galactic Centre.

To infer a possible ejection point and velocity of S5-HVS1, we integrate the orbit of the star backwards in time in the gravitational potential of the Milky Way until the star intersects the Galactic plane \( Z = 0 \) at the location \( X_{\text{pl}}, Y_{\text{pl}} \). Throughout the paper when doing orbit integrations, unless specified otherwise, we adopt the gravitational potential from McMillan (2017), the distance from the Sun to GC of 8.178 kpc (Gravity Collaboration et al. 2019), and Solar velocity of \((U_{\odot}, V_{\odot}, W_{\odot}) = (11.1, 245, 7.25) \) km s\(^{-1}\) (Schönrich et al. 2010; McMillan 2017). To take into account the observational uncertainties in our inference of the ejection site \( X_{\text{pl}}, Y_{\text{pl}} \), when integrating back the orbit of S5-HVS1 we sample the observed uncertainties in radial velocity from \( \delta \) \( \mathbb{N} \), proper motion from Gaia and the distance posterior derived in Section 3.3. The resulting distributions of the Galactic plane ejection coordinates \( X_{\text{pl}}, Y_{\text{pl}} \) together with current heliocentric distance \( D_{\text{hel}} \) and current velocity in the Galactocentric frame \( V_{\text{3D,pl}} \) are shown in Figure 4. The two sets of distributions shown with green and blue correspond to the photometric only distance (Model P) and photometric-spectroscopic distance (Model SP) constraints. We remark that the current heliocentric distance \( D_{\text{hel}} \) distribution is exactly the same as the posterior on \( D_{\text{hel}} \) determined in Section 3.3. While the Figure shows the Monte-Carlo sampling of uncertainties, it is mathematically equivalent to the posterior distribution of \( P(X_{\text{pl}}, Y_{\text{pl}}, D_{\text{hel}}, V_{\text{3D,pl}}; \text{Data}) \) under the model where the star was ejected from MW disk plane (and uninformative priors on \( X_{\text{pl}}, Y_{\text{pl}} \) and ejection velocity).

As expected, the posterior on the S5-HVS1 ejection point is very elongated (almost one dimensional) due to the negligible uncertainties in all parameters but the heliocentric distance. However, we also see that the usage of spectro-photometric distances alleviates this problem somewhat. The current total velocity of the star in the Galactic rest-frame is constrained to be \( V_{\text{3D,pl}} = 1470^{+166}_{-147} \) km s\(^{-1}\) for Model P and \( V_{\text{3D,pl}} = 1687^{+39}_{-37} \) km s\(^{-1}\) for Model SP, while the ejection velocity of the star from the Galactic disk is \( V_{e_j} = 1550^{+190}_{-160} \) km s\(^{-1}\) for Model P, and \( V_{e_j} = 1755^{+24}_{-22} \) km s\(^{-1}\) for Model SP, very similar to the current velocity. The difference between the current velocities and the ejection velocities is small \( \sim 50 \) km s\(^{-1}\) because the impact of the Galactic potential on such a fast moving star is minimal. The inferred ejection point based on the photometric only distance (Model P) is \( X_{\text{pl}} = -2.63^{+1.72}_{-1.54} \) kpc, \( Y_{\text{pl}} = -0.22^{+0.15}_{-0.15} \) kpc, where the values and uncertainties come from 50% and 16%, 84% percentiles of 1-D marginal distributions. However the posterior on \( X_{\text{pl}}, Y_{\text{pl}} \) are strongly non-Gaussian and elongated. Most importantly we see that the Galactic Centre \((X, Y) = (0, 0)\) (shown on Figure 4 by pink dashed lines) is located within the 90% probability contour of the \( X_{\text{pl}}, Y_{\text{pl}} \) distribution. However the peak of the posterior for the ejection point \( X_{e_j}, Y_{e_j} \) is shifted by 2.5 kpc from the Galactic Centre, the fact that the very thin probability contour covers the GC is highly informative and suggestive of a GC origin. If we instead consider the contours for Model SP based on spectro-photometric distances we see that the inference of \( X_{\text{pl}}, Y_{\text{pl}} \) is significantly tighter \( X_{\text{pl}} = -0.3^{+0.39}_{-0.39} \) kpc, \( Y_{\text{pl}} = -0.02^{+0.05}_{-0.04} \) kpc.

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8 In the final stages of preparation of the manuscript, we identified that S5-HVS1 has a distance estimate of \( D_{\text{hel}} = 0.807 \pm 0.148 \) from the STARHorse code (Anders et al. 2019), which is in very good agreement with our photometric-only measurement.

9 The astrometry of S5-HVS1 does not seem to be affected by any astrometric problems according to the re-normalised unit weight error (RU/WE) (Lindegren et al. 2018), which is \( \sim 1.06 \).
Figure 4. The constraints on possible orbital properties and origin of S5-HVS1, assuming that it was ejected from a point in the Galactic plane. $X_{pl}$ and $Y_{pl}$ are the Galactocentric coordinates of the ejection point in the plane. $D_{hel}$ is the current distance to the star and $V_{3D,now}$ is the current velocity of the star in the Galactocentric frame. The blue and green contours and curves refer to the posterior that we obtained while using the photometric only distance (Model P) and spectro-photometric distance (Model SP) respectively. We note that the $D_{hel}$ distributions are exactly the same as in Figure 3 as we reuse the samples from the SED modelling posterior. The dashed lines identify the location of the Galactic Centre. The lines in the contour plots show the 68%, 95% and 99.7% posterior volumes.

and thus our backwards integrations point almost unambiguously at the Galactic Centre $(X_{pl}, Y_{pl}) = (0, 0)$ as the origin of S5-HVS1.\(^\text{10}\)

To further illustrate the strength of evidence supporting an association of S5-HVS1 with the GC we look at the confidence region of the S5-HVS1 origin and compare it to the Solar circle. The left panel of Figure 5 shows the 90% confidence region for S5-HVS1 when relying on spectro-photometric distances (the black contour), and photometric only distances (grey contour). Both of the 90% confidence limits well encompass the GC. We also see that even the less well constrained Model P contour is extremely thin compared to the Solar circle, suggesting that it would be quite unlikely for it to cover the Galactic Centre by random chance. This conclusion applies even more strongly for the minutely thin contours of Model SP as shown by the black line. To formally quantify the statistical significance of the association of S5-HVS1 with the GC, we can use the posterior on $X_{pl}$, $Y_{pl}$ to compute the Bayes factor (see e.g. Trotta 2007) between the hypothesis that the star comes from the GC vs. that it comes from a random point in the Galactic disk. To do this we have to adopt a prior on $X_{pl}$, $Y_{pl}$ for the Galactic disk origin hypothesis. We use the exponential distribution with a scale length of 2.15 kpc, to match the distribution of stellar mass in the disk (Bovy & Rix 2013). With this prior we can then use the Savage-Dickey ratio (Verdinelli & Wasserman 1995) to evaluate the Bayes factor of the two hypotheses: GC and disk.

\[
K = \frac{P(\text{GC}|\text{Data}) \, \pi(\text{disk})}{P(\text{disk}|\text{Data}) \, \pi(\text{GC})} = \frac{P(X_{pl}, Y_{pl} = 0, 0|\text{disk, Data})}{P(X_{pl}, Y_{pl} = 0, 0|\text{disk})}
\]

The Bayes factor is $K = 81$ when we use photometric distances (Model P), and $K = 354$ for the spectro-photometric distances (Model SP). This constitutes strong (Model P) or overwhelming (Model SP) evidence in favour of the Galactic Centre origin. In the calculation, we assumed the same (uniform) priors over ejection

\(^{10}\) While the backward orbit integration done here uses the potential of McMillan (2017), which does not include the SMBH in the Galactic Centre, we have verified that the constraints on the ejection point $(X_{pl}, Y_{pl})$ are completely insensitive to the presence or absence of a $\sim 4 \times 10^6 M_\odot$ BH in the Galactic Centre due to its very small sphere of influence compared to the size of the $(X_{pl}, Y_{pl})$ contours.
The evidence that S5-HVS1 is coming from the GC is almost definitive and is much stronger than for any other hyper-velocity star we know. To illustrate this we take the list of stars from Bouquet et al. (2018, augmented with LAMOST-HVS4 from Li et al. 2018, and J01020100 from Massey et al. 2018), and perform the calculation of the ejection point \( X_{\text{pl}} \), \( Y_{\text{pl}} \) within the plane of the disk (identically to that performed on S5-HVS1), given the existing observational constraints on those stars (position, distances, proper motions and radial velocities). The right panel of Figure 5 shows the 90% confidence contours for a subset of the stars where those contours overlapped significantly with the \( 30 \times 30 \text{kpc}^2 \) region shown. The confidence regions for the S5-HVS1 origin are the barely visible grey and black streaks around the GC compared to all other stars.

Concluding this section, based on strong orbital evidence that points at a region of \( \sim 50 \times 1000 \text{kpc}^2 \) around the GC as the origin of S5-HVS1 (Figure 5) and the large velocity of S5-HVS1 \( V_{\text{3D,now}} \sim 1500 \text{–} 1700 \text{ km s}^{-1} \) that is impossible for a disk runaway star of \( \sim 2 \text{M}_\odot \) (see Tauris 2015), we can conclude that S5-HVS1 was ejected from the Galactic Centre. It is the first star with such a confident identification. In the next section we will analyse what inferences can be made based on this assumption.

5 Galactic Centre Origin

Assuming that S5-HVS1 was ejected from the Galactic Centre, we can now investigate the kinematics of the star further. First we determine the exact ejection velocity and time of flight from the GC
required to match the observations of S5-HVS1, by ejecting the star from the centre of the MW in the potential of McMillan (2017) (without considering the potential of the SMBH itself). This gives a prediction of $\alpha, \delta, \mu_\alpha, \mu_\delta, RV, D_{hel}$ as a function of the ejection velocities $V_x, V_y, V_z$ and travel time $T$. We then write a Normal likelihood function using the observed position, distance, proper motion and RV of S5-HVS1 and their uncertainties (we use a Gaussian approximation to the $log_{10}D_{hel}$ posterior from Section 3.3). We adopt non-informative uniform priors on all the parameters and then sample the posterior using an ensemble sampler. Figure 6 shows the posterior. This model implies an ejection speed of 1798.6 ± 3.1 km s$^{-1}$ with the $z$-component of the velocity being the largest and a total travel time from the GC to the current position of 4.801 ± 0.009 Myr. We note that the constraints on the ejection velocities are now much tighter compared to Figure 4. The reason for this is that postulating that the star is coming from the GC strongly constrains the current distance to S5-HVS1 to be $D_{hel} = 8884 ± 11$ pc and thus makes our spectro-photometric measurement mostly irrelevant.\footnote{Given a star ejected from the Galactic Centre, it is enough to know accurately just the position of the star on the sky and proper motion to exactly determine its heliocentric distance and radial velocity.} We also remark that the measured ejection speed of 1798.6 ± 3.1 km s$^{-1}$ from the GC was computed while ignoring the potential of the SMBH, and thus represents the ejection velocity outside the sphere of influence of the black hole ($\geq 1$ pc). The actual ejection speed of the star depends on how close to the BH the ejection happened, and could easily be as high as $\sim 8000$ km s$^{-1}$ if the ejection happened at a distance of 100 AU from the BH. Assuming a GC origin also allows us to improve the proper motion precision from the one delivered by Gaia $\mu_\alpha \cos \delta = 35.333 ± 0.081$ mas yr$^{-1}$ and $\mu_\delta = 0.617 ± 0.011$ mas yr$^{-1}$. While the $\mu_\alpha \cos \delta$ precision did not improve much, the error-bar on the predicted $\mu_\delta$ is 8 times smaller than Gaia’s. Since the full phase space position of S5-HVS1 becomes very precise when we adopt the GC origin hypothesis, we can look at the geometric position of S5-HVS1 in the Galaxy. This is shown in Figure 7. We see that as expected, S5-HVS1 is mostly moving downwards away from the disk, and that the Sun, Galactic Centre and S5-HVS1 form an almost equilateral triangle with $\sim 8 - 9$ kpc edges.

In this section we will further use the phase space observations of S5-HVS1 to constrain the gravitational potential of the MW, location and kinematics of the Sun in the Galaxy, and assess the possible connection of S5-HVS1 to the stars in the vicinity of Sgr A*.

5.1 Constraining the position and motion of the Sun

Figure 5 shows that the association of S5-HVS1 with the GC crucially depends on the relative geometry between the Sun and the Galactic Centre. For example, a small adjustment of the distance from the Sun to the Galactic Centre ($R_0$) could easily shift the high probability contour $P(x_{GC}, y_{GC})$ away from the GC. Therefore assuming that S5-HVS1 originates in the GC constrains $R_0$ and possibly other Galactic parameters. The idea of constraining the Solar motion as well as the distances to the Galactic Centre have been discussed previously, most notably by Hattori et al. (2018b). To determine these constraints, we construct a forward model where we eject the star from the GC with velocity $V_x, V_y, V_z$ and let it travel in the Galactic potential of McMillan (2017) for the time $T$. We then observe it from the Sun located at a distance of $R_0$ from the Galactic Centre and moving with the velocity $U_\odot, V_\odot, W_\odot$ km s$^{-1}$ (this includes both the speed of the Local Standard of Rest and the peculiar velocity of the Sun). The likelihood of the model is then constructed using the observed 6-D phase measurements of S5-HVS1: position, proper motion, distance and radial velocity. This leads to the following posterior distribution:

$$P(\psi|D) \propto P(D|V_x, V_y, V_z, T, R_0, U_\odot, V_\odot, W_\odot) \pi(V_x, V_y, V_z, T, R_0, U_\odot, V_\odot, W_\odot)\pi(T)$$

(2)

where $\psi$ is the shorthand for all the model parameters $V_x, V_y, V_z, T, R_0, U_\odot, V_\odot, W_\odot$. For this model we focus on constraining $R_0$ and $V_\odot$, so we adopt broad uninformative priors on the distance of the Sun to the Galactic Centre $R_0 \sim U(6.9, 25)$ kpc, and $V_\odot \sim U(200, 290)$ km s$^{-1}$ and informed Normal priors on the other two components of Solar velocity $U_\odot \sim N(11.1, 0.5)$ and $W_\odot \sim N(7.25, 0.5)$ (Schönrich et al. 2010). For the rest of parameters $V_x, V_y, V_z$ we adopt uninformative uniform priors. In principle the model that we have described has a valid posterior that we could sample. However, we have discovered that this posterior is extremely degenerate along one dimension and narrow in another dimension. This is in fact a direct consequence of the elongated contour shape for the constraint on the ejection point $x_{GC}, y_{GC}$ seen in Figure 5. This contour shape and the fact that simultaneous changes of $V_\odot$ and $R_0$ give two degrees of freedom for “moving” the high probability contour in $(x_{GC}, y_{GC})$ space while still covering the GC explains the low degeneracy ridge in the posterior. Furthermore the posterior is also extremely narrow along the time axis, as the orbit needs to pass very close to the precisely known observed position on the sky. It turns out that those features of the posterior make it extremely challenging to sample, so we were unable to do it efficiently.
using either MultiNest, dynesty, ensemble or ensemble parallel tempering samplers (emcee). Our solution to this problem was to adopt an approximation to the posterior where we approximately marginalise over the travel time of the star.

\[ \mathcal{P}(\psi|D) \propto \mathcal{P}(D|V_x, V_y, V_z, T_{\text{max}}, R_0, U_0, V_0, W_0) \]

\[ \pi(V_x, V_y, V_z) \pi(R_0) \pi(U_0, V_0, W_0) \]  

(3)

where \( \psi \) is the shorthand for the model parameters \( V_x, V_y, V_z, R_0, U_0, V_0, W_0 \) and

\[ T_{\text{max}} = \arg \max_T \mathcal{P}(D|V_x, V_y, V_z, T, R_0, U_0, V_0, W_0) \]

Thus \( T_{\text{max}} \) is the travel time that maximises the likelihood (or approaches the current phase-space constraint of S5-HVS1 the most closely). We find the \( T_{\text{max}} \) for each set of parameters by doing 1-D maximisation using the Brent algorithm (Brent 2013). The resulting posterior on \( V_x, V_y, V_z, R_0, U_0, V_0, W_0 \) is then sampled using an ensemble sampler with 192 walkers.

The left panel of Figure 8 shows the 2-D marginalised posterior on two of the parameters – heliocentric distance to the GC and the Y component of the Solar velocity (\( V_y \)). As before blue lines correspond to Model P (photometric only distance), and green lines to Model SP (spectro-photometric distance). The red bands show the 1-sigma constraints from Gravity Collaboration et al. (2019). As expected the figure shows a degeneracy between parameters which is almost complete when using the less constrained photometric only distances, however with spectro-photometric distances the degeneracy is significantly reduced.

We note that even with the spectro-photometric distances of S5-HVS1 we cannot strongly constrain both \( V_y \) and \( R_0 \) (as the green contours on Figure 8 are quite large). However, if we adopt the prior on the Galacticocentric distance from Gravity Collaboration et al. (2019), we obtain the posterior on \( V_y \) shown on the right panel of the figure. \( V_y \) is constrained to be \( 246.1 \pm 5.3 \) km s\(^{-1}\). Those constraints also do not depend significantly on whether we use spectro-photometric or photometric only distances as we slice the posterior shown on the left panel of the figure across the distance degeneracy. The \( V_y \) measurement is competitive with and entirely independent from the \( 247.4 \pm 1.4 \) km s\(^{-1}\) constraint from Gravity Collaboration et al. (2019). If we instead use the prior on \( V_x \) from Gravity Collaboration et al. (2019) to constrain the distance to the Galactic Centre (marginalising over the \( x \)-axis on Figure 8), we obtain \( R_0 = 8.12 \pm 0.23 \) kpc.

While Figure 8 may look somewhat underwhelming compared to the Gravity Collaboration et al. (2019) measurements, we highlight that our measurement was done with one single star. The shape of the degeneracy in \( U_0, V_0, W_0, R_0 \) space is specific to the position of the star on the sky, and so if we had a second star then the combined constraints would be significantly more precise and likely comparable in precision to Gravity Collaboration et al. (2019)\(^{12}\). Another reason for optimism is that future Gaia data releases and high-resolution spectroscopic follow-up will narrow the uncertainties on the proper motion and distance of S5-HVS1 and thus tighten our constraints on the Solar motion and position in the Galaxy.

\(^{12}\) In fact in this paper we did not consider determining \( U_0, W_0 \), because they are significantly less constrained than \( V_0 \). That can be easily seen because of the shape of the contour of \( \mathcal{P}(X_{\text{pl}}, Y_{\text{pl}}) \) on Figure 5. The contour is the thinnest in the direction of solar rotation and is larger by a factor of ten in the \( U \) direction.

![Figure 8. Left panel: The 2-D marginalised posteriors on the heliocentric distance to the GC (\( R_0 \)) and y-component of Solar velocity in the Galaxy as inferred from S5-HVS1. The contours correspond to the 68% and 95% posterior volumes. Blue lines on both panels refer to quantities derived from our photometric only distance (Model P), while the green ones refer to the more precise spectro-photometric distances (Model SP). The red bands shows the constraints on \( R_0 \) and \( V_y \) from Gravity Collaboration et al. (2019). Right panel: 1-D marginal posteriors on the y-component of Solar velocity in the Galactic rest-frame after adopting a prior on \( R_0 \) from Gravity Collaboration et al. (2019). The inferred value is \( V_y = 246.1 \pm 5.3 \) km\,s\(^{-1}\).](image-url)
motion precision, S5-HVS1 cannot yet be used to constrain the MW gravitational potential. One additional reason for the current lack of constraining power from S5-HVS1 is that, because we do not know the actual ejection velocity from the BH, we do not constrain the total deceleration of the star, but only deviations of the trajectory from a straight line. For meaningful potentials consistent with the existing data, the deviations from a straight line for a ~ 2000 km s\(^{-1}\) star flying for ~ 5 Myr are within a few tens of parsecs (listed above) and thus within the current uncertainties of the S5-HVS1 trajectory. With the improvement in proper motion precision from future Gaia data we expect, however, that constraints on the MW halo flattening will be possible.

5.3 S5-HVS1 ejection by Sgr A*

Given an almost certain GC origin of S5-HVS1, here we discuss possible implications for the ejection by Sgr A*. We focus on the Hills (1988) mechanism involving a three-body interaction of a stellar binary with the SMBH leading to one star being ejected. There are other mechanisms involving binary black holes (Yu & Tremaine 2003; Levin 2006) and a SMBH surrounded by a cluster of stellar mass black holes (O’Leary & Loeb 2008), and we will discuss some of them later.

The first question we address is what are the expected properties of the binary required to produce the very high ejection speed of S5-HVS1. To infer this we use the results of Bromley et al. (2006), who parameterized the distribution of ejection velocities as a function of the black hole mass and binary parameters (see equations 1-4 of Bromley et al. 2006). We adopt a black hole mass of 4.1 x 10\(^6\) M\(_\odot\) from Gravity Collaboration et al. (2018), fix the mass of S5-HVS1 to the observed value 2.35 M\(_\odot\) (see Table 2) and adopt an ejection velocity of 1798 ± 3 km s\(^{-1}\). The remaining parameters required to compute the ejection velocity distribution are the semi-major axis of the binary \(a\), the mass of the second star \(M_2\) and the minimum approach distance \(R_{\text{min}}\) between the binary and the SMBH. We adopt a log-uniform distribution over the binary separation and the Chabrier (2005) IMF prior on the mass of the secondary, and \(\pi(R_{\text{min}}) \sim R_{\text{min}}\) prior for the minimum approach distance (see Bromley et al. 2006, for details). We require that the semi-major axis of the binary is larger than 2.5 R\(_\odot\), which is approximately the expected radius of a star with a mass of ~ 2.35 M\(_\odot\) (Boyajian et al. 2013), and that the radius of S5-HVS1 is smaller than its tidal radius at the closest approach between the binary and the SMBH (\(R_{\text{min}}\)). This limits the minimal separation of the binary and the SMBH \(R_{\text{min}}\) to be \(\gtrsim 1.4\) au.

Figure 9 shows our inferred probability distribution of the semi-major axis of the binary and the mass of the second star. The distribution shows that in order to produce S5-HVS1 we need a former binary companion with mass 0.9 M\(_\odot\) \(\lesssim M_2 \lesssim 16\) M\(_\odot\), where low mass secondaries require an extremely tight separation of only ~ 0.06 au, while if the secondary is massive, the semi-major can be as much as ~ 0.63 au. The orbital periods of these binaries would range from 3 to 40 days. These ranges correspond to the 68% confidence interval of the posterior. The binary parameters that we obtain are certainly possible (see e.g. Raghavan et al. 2010; Moe & Di Stefano 2013), however, we expect these binaries to be quite rare.

5.4 S5-HVS1 and stars around Sgr A*

Given the certainty of the S5-HVS1 association with the Galactic Centre, it is interesting to assess if S5-HVS1 is related to any other structures known around the GC. The main stellar structure near the centre of the MW is the nuclear star cluster (Becklin & Neugebauer 1968; Launhardt et al. 2002) with the Sgr A* SMBH at the centre. The central part of the star cluster consists of the so-called S-stars whose dynamics are dominated by the SMBH, and that orbit around it with periods from a few years to a few hundred years (Ghez et al. 2005; Gillessen et al. 2009). These stars are known to be massive and young (Genzel et al. 2010; Lu et al. 2013) and we do not yet know how they came to be where they are. Furthermore, the cluster of stars around Sgr A* is known to have substructure in the form of a coherently rotating small disk of young stars (the so-called clock-wise or CW disk) (Levin & Beloborodov 2003; Paumard et al. 2006; Bartko et al. 2009; Yelda et al. 2014; Gillessen et al. 2017).

The reason why S5-HVS1 can be potentially associated to some structures in the centre is that if the star has been produced by the Hills mechanism, then we expect that the direction of HVS’s flight should be approximately aligned (Lu et al. 2010; Zhang et al. 2010) with (i) the orbital plane of the original binary around the SMBH; and (ii) the orbital plane of the secondary star captured by the SMBH after the binary disruption (unless the secondary was swallowed by the black hole and/or produced a tidal disruption event). Thus we can hope to either identify a possible progenitor population of the S5-HVS1 binary or perhaps directly pinpoint the star that was previously paired to S5-HVS1 and still orbits Sgr A*.

To check for possible association with the S-stars, we consider a set of possible orbital planes around the black hole that are aligned with the S5-HVS1 direction of flight. This set is clearly a 1-D manifold as there are infinitely many planes aligned with the vector pointing from the GC to S5-HVS1. On Figure 10 we show the distribution of poles (or angular momentum directions) for this set of orbits by a red curve. The coordinate system of the figure is the positional angle of the ascending node of the orbit and the angle between the orbital plane with respect to the vector from the Sun to the GC. Therefore the orbits seen edge-on from the Sun would occupy the equator on the figure, while face-on orbits would correspond to either the north or the south pole of the figure depending on the direction of rotation. On the figure we also overplot by blue circles the orientations of orbits (specifically the direction of their angular momenta) for stars around Sgr A* from Gillessen et al. (2017). Thus if the S5-HVS1 has been produced by the Hills mechanism and the secondary star was captured on an orbit around the BH, then the red curve should pass near the current orbital plane.
Here we address the multiple open questions that the discovery of S5-HVS1 poses. First, we compare S5-HVS1 to the other HVS. The main property that distinguishes S5-HVS1 from the rest of the hyper-velocity stars is its unusually high velocity. If we exclude the recently discovered D9 white dwarfs produced in SNIa-like explosions (Shen et al. 2018), the velocity of S5-HVS1 is almost a factor of two larger than the velocity of any other known HVS. Figure 11 shows the distribution of likely ejection velocities from the Galactic Centre for other HVS. Here we use the same set of stars from Boubert et al. (2018) as shown on Figure 5, and select a subset of those which can be well described ($\chi^2 < 20$) as being ejected from the Galactic Centre based on proper motion, position, distance and radial velocity. The figure shows how much of an outlier S5-HVS1 is, in particular because of the apparent clumping of previously known HVS at 800–1000 km s$^{-1}$, which begs the question whether S5-HVS1 was produced using the same mechanism as other HVS. Another difference between S5-HVS1 and other HVS is that it is an A-type star, and thus is somewhat cooler, lower mass and later spectral type than the classical B-type hyper-velocity stars (Brown 2015). It is also brighter and much more nearby than the majority of the faint, blue HVS that have been discovered in the Northern sky.

One possible interpretation of these differences between S5-HVS1 and previously known HVS is that $S^5$ was just very lucky to stumble on a very rare object. However the other explanation may be related to the somewhat lower mass and redder colour of S5-HVS1 $g-r = -0.27$, which is close to the colour boundary $g-r \sim -0.3$ of dedicated searches (Brown et al. 2006, 2009); this boundary minimises contamination because MS and BHB stars start to overlap at this colour. This may be the reason why previous spectroscopic searches missed lower mass/redder stars like S5-HVS1. However, since the Sloan Digital Sky Survey (SDSS; York et al. 2000; Yanny et al. 2009) did observe a large number of blue A-type stars in the range $-0.4 < g-r < 0$ and did not find anything close to S5-HVS1, it is useful to compare the number of objects spectroscopically observed by SDSS to $S^5$. In fact, surprisingly, SDSS (DR9; Ahn et al. 2012) has observed spectroscopically only ~7 times more blue, distant (with small parallax $\pi < 3.3 \sigma_\pi$) stars in the $-0.4 < g-r < -0.2$ and $16 < g < 18$ colour-magnitude range than $S^5$ did (1445 vs 202). Thus the SDSS non-detection of an S5-HVS1-like star is not in significant disagreement with the $S^5$ discovery.

Another possible explanation of the S5-HVS1 discovery has to do with its proximity, as the star is closer by a factor of several compared to other HVS. Why would closer HVSs be potentially noticeably faster or have a different velocity distribution? For this to happen it would require that the ejection mechanism of HVS is not operating at a constant rate and/or doesn’t eject the same spectrum of HVS over time. In the canonical Hills (1988) mechanism where the loss cone of the SMBH is populated by slow scattering processes, such rapid changes would be problematic. However, as the presence of young (only few Myr old) stars and substructures near the GC indicate, the Galactic Centre has had a very active recent history; e.g. it is likely that the GC had an accretion event of a giant molecular cloud a few Myr ago that formed new stars (Bonnell & Rice 2008; Lucas et al. 2013) that were then distributed in a disk around the SMBH. If that is the case, that accretion event could have been a source of binaries for the Hills mechanism, producing an excess of stars in the orbital plane of accretion and an increased rate of HVS ejections a few Myr ago. In such a scenario, HVSs like S5-HVS1 could serve as timers and indicators of orientation of large accretion events happening near the GC. To test this hypothesis we will, however, need to find more stars with similar travel times as S5-HVS1. It is remarkable that the age of S5-HVS1 ejection is close to both the age of the disk of young stars around the GC (Lu et al. 2013) and the age of the Fermi bubbles (Bland-Hawthorn & Lucas et al. 2013).
Given the measured distance, proper motion and radial velocity, the total velocity of the star in the Galactic rest frame on S5-HVS1 to constrain the distance from the Sun to the Galactic Centre and the Galactic Solar velocity. We have not been able to constrain those simultaneously, mainly due to the precision of the distance determination to S5-HVS1. However, in the future, the combination of such constraints from multiple S5-HVS1-like stars (see Figure 8) will resolve the existing degeneracies and should provide extremely precise measurements of the geometric and kinematic Galactic parameters. We believe that with the upcoming Gaia data as well as future spectroscopic surveys like WEAVE (Dalton et al. 2014), 4MOST (de Jong et al. 2014) and DESI (DESI Collaboration et al. 2016), the discovery of more HVS similar to S5-HVS1 is guaranteed. Furthermore, while with S5-HVS1 we were currently not able to put constraints on the gravitational potential due to the very short flight time and loose proper motion constraint, with the next Gaia data release that will increase the proper motion precision by a factor of few as well as deliver new HVSs, we think we will be able to start constraining the potential with individual HVSs as predicted by Gnedin et al. (2005).

One other interesting prospect for the future of HVS science that we did not explore in this paper, but which may be promising, is that HVS could become probes of substructure and particularly DM substructure in the Galaxy, similar to stellar streams (Yoon et al. 2011; Erkal et al. 2016) or lensing (Vegetti et al. 2012). The reason for this is that for HVS that were ejected from the GC we know the orbit exactly, as it must connect to the Galactic Centre. Thus if we imagine a large collection of HVS travelling throughout the Galaxy, we expect that some of those trajectories will be affected by various external perturbations, including massive perturbers such as the Large Magellanic Cloud or Sagittarius Dwarf Spheroidal Galaxy, but also potentially smaller DM halos and globular clusters in the halo. Although we expect the effect of these perturbations to be quite small due the high velocity of the stars, if we have enough of these stars and they have high accuracy phase-space measurements, then we could say something about the mass substructure in the Galaxy. As an example, a $10^5 M_\odot$ point-mass perturbing a hyper-velocity star travelling at 2000 km s$^{-1}$ with an impact parameter of 0.5 kpc will produce a velocity offset of $\sim$ 1 km s$^{-1}$ (Binney & Tremaine 2011) perpendicular to the trajectory of the HVS, or equivalently an offset of $\sim$ a few parsecs in the trajectory. While these offsets are small, the velocity accuracy is within what Gaia proper motions will provide for objects brighter than $G \sim$ 17 within 10 kpc.

Finally, let us consider the effect of future Gaia data releases on S5-HVS1. The main improvement will come from much higher precision parallaxes and proper motions, which are expected to better constrain the orbit of S5-HVS1. In advance of Gaia DR3, we predict that the true proper motions and parallax of S5-HVS1 are $\mu_r \cos \delta = 35.333 \pm 0.080$ mas yr$^{-1}$, $\mu_\delta = 0.617 \pm 0.011$ mas yr$^{-1}$ and $\sigma = 0.11$ mas (corresponding to a distance of 8.828 kpc). Time will tell whether these predictions based on the assumption of a GC origin will hold.

7 CONCLUSIONS

- Using data from the $S^5$ spectroscopic survey we have identified a star with a radial velocity of $\sim$ 1020 km s$^{-1}$ without any signs of binarity across a year of observations.
- Analysis of the spectra and photometry of the star shows that it is likely an A-type $\sim$ 2.35 $M_\odot$ Main Sequence metal-rich star at a distance of $\sim$ 9 kpc.
- Given the measured distance, proper motion and radial velocity, the total velocity of the star in the Galactic rest frame
is $1755 \pm 45$ km s$^{-1}$, making it the third fastest hyper-velocity (unbound) star in the Galaxy after the D$^0$ white dwarfs (Shen et al. 2018).

- Backtracking the current phase-space position of S5-HVS1 to the MW disk points at a small elongated region of $\sim 50 \times 1000$ pc$^2$ that contains the Galactic Centre. This provides incredibly strong evidence that the star was ejected from the Galactic Centre at speed of $\sim 1800$ km s$^{-1}$ around $\sim 4.8$ Myr ago.

- If S5-HVS1 was ejected from the GC then we can constrain the distance to the Galactic Centre and the Solar velocity. If we assume the Gravity Collaboration et al. (2019) prior on $R_0$, then our constraint on the y-component of solar velocity is $V_\odot = 246.1 \pm 5.3$ km s$^{-1}$, and, vice-versa, if the Gravity Collaboration et al. (2019) prior is used on $V_\odot$, it leads to an $R_0$ constraint of 8.12 $\pm$ 0.23 kpc. Due to the short flight time and non-negligible proper motion uncertainties, the star currently can not yet constrain the MW gravitational potential.

- The direction of the S5-HVS1 ejection is curiously aligned with the disk of young stars around the Sgr A* suggesting a possible connection. This may mean that the star has been ejected in the same event that lead to the disk’s formation.

- The fact that S5-HVS1 was ejected with a velocity almost twice that of all other known HVS potentially originating from the GC poses two questions: were all the known HVS produced by the same mechanism and has the HVS velocity spectrum been constant in time?

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Software: numpy (van der Walt et al. 2011), scipy (Jones et al. 2001), matplotlib (Hunter 2007), astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018), emcee (Foreman-Mackey et al. 2013), gala (Price-Whelan 2017), g3c (Koposov & Bartonov 2006), isochrones (Morton 2015) fastKDE (O’Brien et al. 2016), dynesty (Speagle 2019), pymultinest (Buchner et al. 2014), pySM (Pérez & Grainger 2007), chainconsumer (Hinton 2016), rebound (Rein & Liu 2012), multiNest (Feroz et al. 2009), RvSpeckFit (Koposov 2019), schwimmbad (Price-Whelan & Foreman-Mackey 2017)

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