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Letter to the Editor

SDSS J013655.91+242546.0 – an A-type hyper-velocity star from the outskirts of the Galaxy⋆,⋆⋆

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ABSTRACT

Context. Hyper-velocity stars (HVS) are moving so fast that they are unbound to the Galaxy. Dynamical ejection by a supermassive black hole is favoured to explain their origin.

Aims. Locating the place of birth of an individual HVS is of utmost importance to understanding the ejection mechanism.

Methods. SDSS J013655.91+242546.0 (J0136+2425 for short) was found amongst three high-velocity stars (drawn from a sample of more than 10 000 blue stars), for which proper motions were measured. A kinematical as well as a quantitative NLTE spectral analysis was performed. When combined with the radial velocity (RV) and the spectroscopic distance, the trajectory of the star in the Galactic potential was reconstructed.

Results. J0136+2425 is found to be an A-type main-sequence star travelling at ≈590 km s^{-1}, possibly unbound to the Galaxy and originating in the outer Galactic rim nowhere near the Galactic centre.

Conclusions. J0136+2425 is the second HVS candidate with measured proper motion, besides the massive B star HD 271791, and also the second for which its proper motion excludes a Galactic centre origin and, hence, the SMBH slingshot mechanism. Most known HVS are late B-type stars of about 3 $M_{\odot}$. With a mass of 2.45 $M_{\odot}$, J0136+2425 resembles a typical HVS far more than HD 271791 does. Hence, this is the first time that a typical HVS is found not to originate in the Galactic centre. Its ejection velocity from the disk is so high (550 km s^{-1}) that the extreme supernova binary scenario proposed for HD 271791 is very unlikely.

Key words. stars: kinematics – stars: individual: SDSSJ013655.91+242546.0 – stars: atmospheres – line profiles

1. Introduction

Stars travelling so fast that they escape from the Galaxy are an inevitable consequence of the presence of a supermassive black hole (SMBH) in a dense stellar environment (Hills 1988) such as the Galactic centre (GC). Hills (1988) coined the term hyper-velocity star (HVS) for such an object. It took a long time until Brown et al. (2005), Hirsch et al. (2005) and Edelmann et al. (2005) discovered the first three HVSs serendipitously and the interest in these stars grew tremendously. Systematic searches for HVSs took advantage of the huge *SDSS* database (Adelman-McCarthy et al. 2008) for target selection and revealed a population of HVSs; the latest compilation lists 16 of these stars (Brown et al. 2009a). These surveys are based on RV measurements alone. The known HVSs are non-uniformly distributed on the sky, as are their travel times. Brown et al. (2009b) argue that this anisotropy supports their common origin being the Galactic centre, while Abadi et al. (2009) point out that the overdensity of HVSs in the constellation Leo suggests that the anisotropic distribution and preferred travel time are the result of the tidal disruption of a dwarf galaxy in the Galactic potential.

Another issue is the distance of a HVS star, because blue horizontal branch (BHB) stars can not be easily distinguished from main-sequence (MS) stars for the HVSs in question since both types of stars populate the same region in the $T_{\rm eff}$-log g-diagram (Heber et al. 2008b), but have different distances. It is generally assumed that the stars are main-sequence and not blue horizontal branch stars. Detailed spectroscopic analyses have confirmed these assumptions for HVS1, HVS3, HVS7, and HVS8 (Przybilla et al. 2008b,c; Heber et al. 2008b; López-Morales & Bonanos 2008). In the absence of proper motion measurements, the trajectories have not been derived for any individual HVS so far. Heber et al. (2008a) succeeded in investigating the trajectory of the high-velocity B star HD 271791 from accurate proper motions, radial velocity, and spectroscopic distance. The star was found to be probably unbound to the Galaxy and to originate in the outer rim of the Galaxy rather than in its centre, demonstrating that a mechanism other than that of Hills (1988) must operate. Hence, it is rewarding to measure proper motions of high-velocity stars. Xue et al. (2008) presented radial velocities for more than 10 000 blue stars from the *SDSS* , which are a mix of blue horizontal branch, blue straggler, and main-sequence stars with effective temperature between roughly 7000 and 10 000 K according to their colours. We focused on the 11 fastest stars in terms of large positive Galactic rest-frame (GRF) velocities to unravel their nature, distance, and kinematics from detailed quantitative spectral analyses and astrometry. Three stars exhibited significant proper motions[1]. Here we

⋆ Based on data collected at the European Southern Observatory, Chile. Program ID: 082.D-0649.

⋆⋆ Based on observations at the 3.5 m telescope at DSAZ observatory (Calar Alto) in Spain. Program ID: H09-3.5-028.

[1] Two of the stars are found to be a metal-poor straggler of population II and a spectroscopic binary, as described in a forthcoming paper.

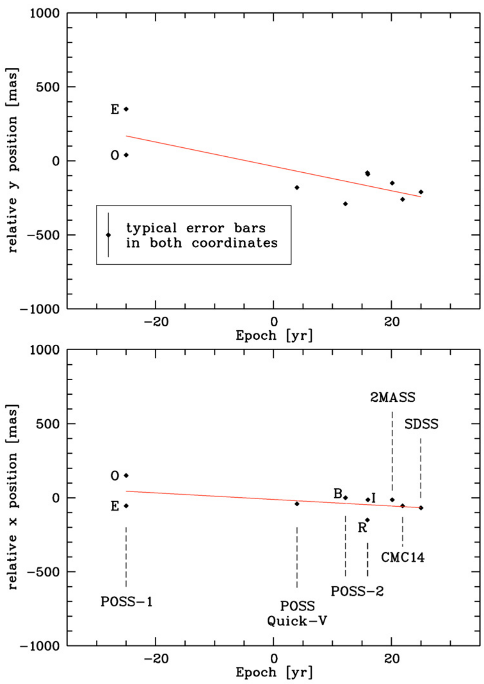

Fig. 1. Linear fit of the position measurements for J0136+2425, whereas 1979.74 is the zero epoch.

report that J0136+2425 is an A-type main sequence star travelling at ≈590 km s^{-1}, possibly unbound to the Galaxy and originating in the outer Galactic disk.

2. Target selection and proper motion

We selected all stars with GRF velocities $\upsilon_{\rm GRF} > +350$ km s^{-1} from the RV-based sample of Xue et al. (2008) and obtained 11 targets for which we attempted to measure proper motions. All available independent position measurements on Schmidt plates (APM – McMahon et al. 2000; SSS – Hambly et al. 2001) were collected and combined with the SDSS and other available positions (CMC14 Carlsberg-Meridian-Catalog 2006; 2MASS – Cutri et al. 2003; UKIDSS – Lawrence et al. 2007) to perform a linear proper motion fit. However, there were even more Schmidt plate measurements from up to 14 different epochs in the case of overlapping plates of the Digitised Sky Surveys[2]. FITS images of 15 by 15 arcmin size were extracted from all available plates and ESO MIDAS tool center/gauss was used to measure positions. For this purpose, we selected compact background galaxies around each target, identified from SDSS, to transform the target positions in all the Schmidt plates to the SDSS system. The small fields allowed us to apply a simple model (shift+rotation) and to achieve an improved fit for all our targets (see Fig. 1). Significant proper motions were found for the three brightest stars only. For J0136+2425, we obtain $\mu_\alpha \cos(\delta) = -2.2 \pm 1.3$ mas yr^{-1} and $\mu_\delta = -8.2 \pm 2.2$ mas yr^{-1}.

3. Observations and quantitative spectroscopy

In order to exclude RV variability, we reobserved J0136+2425 at ESO with EFOSC2 mounted on the NTT in October 2008 and with the TWIN spectrograph at the 3.5 m telescope on Calar Alto in July 2009; during the latter run, six spectra for J0136+2425 distributed over three days were obtained. Radial velocities were derived by χ^2-fitting suitable synthetic spectra over the full spectral range. Since we used many spectral lines, our results differ from that of Xue et al. (2008) who used the Hδ line only. The radial velocities from individual spectra agree to within their respective error limits, indicating that the star is not RV variable within a few kilometers per second on timescales of days.

A quantitative analysis was carried out following the hybrid NLTE approach discussed by Przybilla et al. (2006). The effective temperature $T_{\rm eff}$ and the surface gravity $\log g$ were determined by fits to the Stark-broadened Balmer and Paschen lines and the ionisation equilibrium of Mg I/II. The stellar metallicity were derived by model fits to the observed metal-line spectra. Results are listed in Table 1 and a comparison of the resulting final synthetic spectrum with observations in the selected regions around the Balmer lines, the higher Paschen series, Mg II λ4481 Å, the Mg I b and the near-IR O I triplets, is shown in Fig. 2. Overall, excellent agreement is obtained for all strategic spectral lines throughout the entire wavelength range. The uncertainties in the stellar parameters were constrained by the quality of the match of the spectral indicators within the given S/N limitations.

Its $T_{\rm eff}$ and gravity places J0136+2425 on the main sequence (see Fig. 3). In addition the star is rapidly rotating at 250 km s^{-1} and its metallicity is solar, which strengthens the conclusion that it is an intermediate-mass A-type main-sequence star of 2.45 $M_\odot$ as derived by comparing the position of the star to predictions of the evolutionary models of Schaller et al. (1992).

In Fig. 3, we compare the position of J0136+2425 in the ($T_{\rm eff}$, $\log g$)-diagram to those of five late B-type HVSs for which these parameters are available (Przybilla et al. 2008b,c; Heber et al. 2008b; López-Morales & Bonanos 2008) as well as those of the massive B star HE 0437−5439 originating in the LMC, and the B giant HD 271791. The vast majority of HVSs are of late B type because they were discovered by targeted searches. Hence, we shall term them typical HVSs. J0136+2425 is slightly cooler and less massive than the other known HVS. However, its mass and evolutionary lifetime is similar to that of the typical HVSs (3–4 $M_\odot$, ≈100 Myr), while HE 0437−5439 and HD 271791 are far more massive (9–11 $M_\odot$) and short-lived (≈20 Myr).

4. Distance, kinematics, and errors

Using the mass, effective temperature, gravity, and extinction-corrected apparent magnitude, we derive the distance following Ramspeck et al. (2001) using the fluxes from the final model spectrum. The distance error is dominated by the gravity error.

Table 1. Results of the spectroscopic and kinematic analysis of J0136+2425.

V (mag)[a]	16.17 ± 0.02	$E(B-V)$ (mag)[b]	0.16 ± 0.02
$\mu_\alpha \cos(\delta)$ (mas yr^{-1})	−2.2 ± 1.3	μ_δ (mas yr^{-1})	−8.2 ± 2.2
$T_{\rm eff}$ (K)	9100 ± 250	$\log g$(cgs)	3.90 ± 0.15
$[M/H]$	0.0	$M/M_\odot$	2.45 ± 0.20
$\upsilon_{\rm rad}$ (km s^{-1})	324.3 ± 5.9	$\upsilon_{\rm rot} \sin i$ (km s^{-1})	250
d (kpc)	10.90 ± 2.00	$\upsilon_{\rm grf}$ (km s^{-1})	587^{+144}_{-89}
$\upsilon_{\rm ej}$ (km s^{-1})	551	$\upsilon_{\rm esc}$ (km s^{-1})	466
TOF (Myr)	12 ± 1.3	$t_{\rm evol}$ (Myr)	245

[a] The visual magnitude derived following Jordi et al. (2006); [b] The interstellar colour excess $E(B-V)$ was determined by comparing the observed colours to synthetic ones from the model spectral energy distribution.

[2] http://archive.stsci.edu/cgi-bin/dss_plate_finder

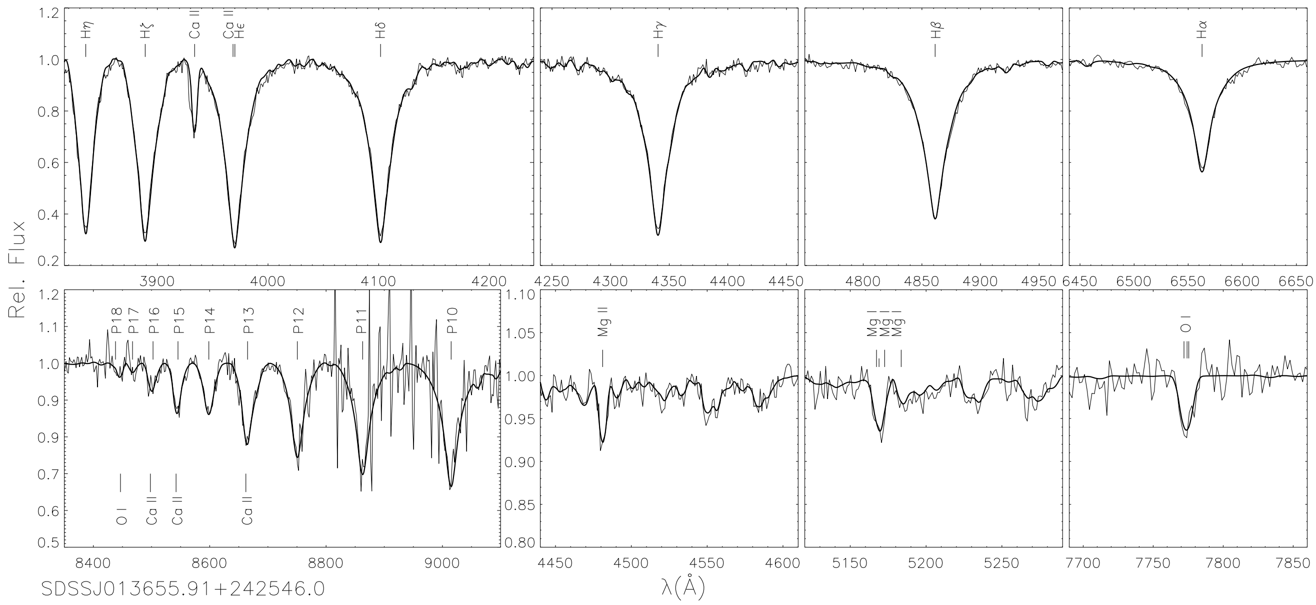

Fig. 2. Comparison of NLTE spectrum synthesis (thick line) with observation (thin wiggly line) for J0136+2425.

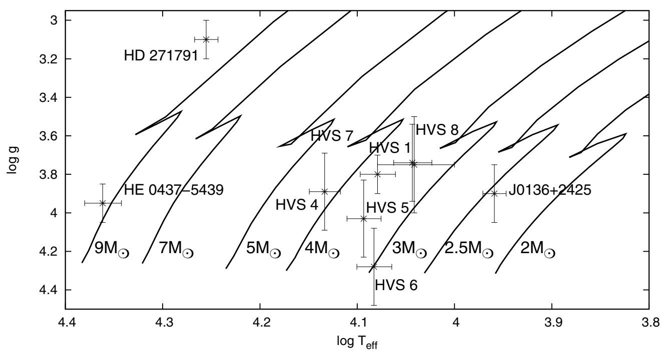

Fig. 3. J0136+2425 in the ($T_{\rm eff}$, $\log g$) diagram with evolutionary tracks of Schaller et al. (1992) for solar metallicity.

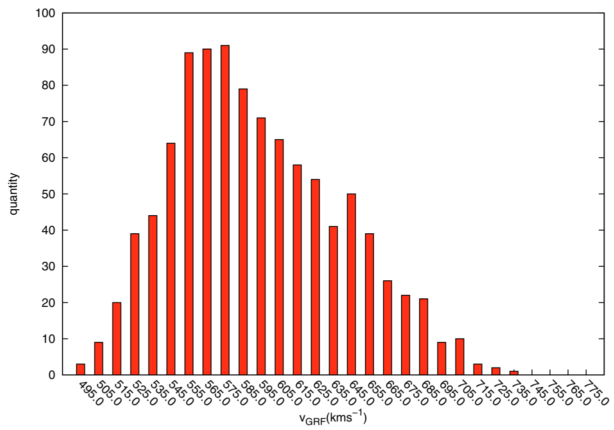

Fig. 4. Galactic rest-frame velocity distribution for J0136+2425.

Applying the Galactic potential of Allen & Santillan (1991), we calculated orbits and reconstructed the path of the star back to the Galactic plane with the program of Odenkirchen & Brosche (1992). The distance of the GC from the Sun was adopted to be 8.0 kpc and the Sun's motion with respect to the local standard of rest was taken from Dehnen & Binney (1998). Since the RV is well known, the error in the space motion is made up of that of the distance, which is controlled mainly by the gravity error, and those of the proper motion components. Varying these three quantities within their respective errors by applying a Monte Carlo procedure with a depth of 1000, we determined the intersection area of the trajectories with the Galactic plane and the time-of-flight. From these Monte Carlo simulations, we derived the median GRF velocities at the present location and their distibution (see Fig. 4) and compared these with the local escape velocity calculated from the Galactic potential of Allen & Santillan (1991).

For J0136+2425, the GRF velocity of 587^{+144}_{-89} km s^{-1} slightly exceeds the local escape velocity. Whether the star is bound to the Galaxy depends on the Galactic potential adopted, in particular for the dark matter halo, as pointed out by Abadi et al. (2009). Allen & Santillan (1991) adopted a halo mass out to 100 kpc of $M_{\rm Halo} = 8 \times 10^{11}$ $M_{\odot}$. Xue et al. (2008) derived a somewhat lower mass whereas Abadi et al. (2009) favoured a higher one of $M_{\rm Halo} = 1.83 \times 10^{12}$ $M_{\odot}$. If the former were correct, J0136+2425 would be unbound, while it would be bound in the latter case. As can be seen in Fig. 5, its place of origin is found to be in the outer part of the Galactic plane at Galactic radii between 12.5 kpc and 18 kpc, nowhere near the GC. The time of flight (12 ± 1.3 Myr) is much shorter than the star's lifetime (450 Myr).

5. Conclusion

We have reported the quantitative spectral analysis of a high-velocity star from the sample of faint blue stars in the halo of Xue et al. (2008). The radial velocity, proper motion, and spectroscopic distance were derived and a detailed kinematical analysis was performed using the Galactic potential of Allen & Santillan (1991).

J0136+2425 was found to be a rapidly rotating A star of solar composition and therefore classified as a main-sequence star of 2.45 $M_{\odot}$. The kinematic analysis excludes an origin at the GC and hence the Hills mechanism for ejection of the star. Its

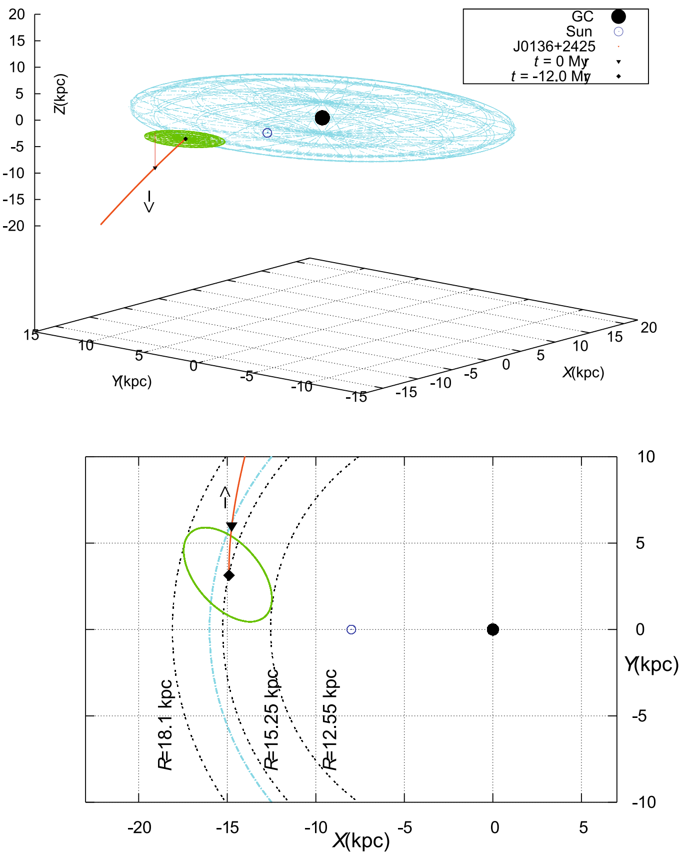

Fig. 5. *Upper panel*: trajectory for J0136+2425 with place of birth marked in green (3σ-error), relatively to the Galactic disk (light blue). *Lower panel*: galactic disk (light blue) projection of the trajectory for J0136+2425 and intersection of the bunch of trajectories (green). Note that the GC is far from the plane intersection area.

place of origin was found to be in the outer part of the Galactic plane at Galactic radii between 12.5 kpc and 18 kpc. This is very similar to the case of the massive B star HD 271791 (Heber et al. 2008a), which was the first ultra-high-velocity star whose proper motion excludes a GC origin. The ejection mechanism for the star was proposed to be an extreme binary supernova, which also explained its enrichment in α elements. However, we find no evidence of α-enhancement in J0136+2425 from the existing spectra. The star is more metal-rich than expected on average for an object born at such a large Galactocentric distance. Due to the presence of Galactic abundance gradients (Rudolph et al. 2006), we expect the outer parts of the Galaxy to be less metal-rich than the Sun. The metallicity of J0136+2425 is compatible with the high end of the abundance distribution in the outer disk.

The required ejection velocity from the disk is so high (550 km s^{-1}) that an extreme supernova binary scenario as proposed for HD 271791 (Przybilla et al. 2008a) is very unlikely.

Most known HVS are late B-type stars of about 3 $M_\odot$. With a mass of 2.45 $M_\odot$, J0136+2425 resembles such a typical HVS much more than HD 271791 ($M = 11\ M_\odot$) does. Hence, this is the first time that a typical HVS is found not to originate in the GC and excludes the SMBH slingshot mechanism. Hence, typical HVS may have been ejected by different mechanisms other than that proposed by Hills.

Once more, this calls for an alternative ejection scenario to the Hills mechanism such as dynamical ejection from clusters or binary supernovae (see Gvaramadze et al. 2009). Hence, we are left with the dynamical ejection scenario or tidal disruption of a satellite galaxy, as proposed by Abadi et al. (2009). They noticed a clustering of more than half of the known HVS in a region of 26°-diameter in the constellation of Leo ($l_{\rm II} \approx 230°$, $b_{\rm II} \approx 60°$). They suggested that if these star stems from a disruption event of a dwarf galaxy, more high velocity stars should be found in that area. However, J0136+2425 ($l_{\rm II} = 136°$, $b_{\rm II} = -37°$) is located far from Leo and is therefore probably unrelated.

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