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LETTER TO THE EDITOR

The B-type giant HD 271791 in the Galactic halo

Linking run-away stars to hyper-velocity stars*

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ABSTRACT

Context. Young, massive stars have been found in the distant Galactic halo. Dynamical ejection from the Galactic disc has been suggested as the origin of these "run-away stars". The so-called hyper-velocity stars have been found to travel so fast that they are unbound to the Galaxy. Only a supermassive black hole (SMBH) appears to be able to accelerate the stars to such high velocities, which suggests that the Galactic centre is their place of origin.
Aims. We revisit the run-away B star HD 271791 to determine its nature and origin.
Methods. High-resolution optical echelle spectra are analysed using LTE model atmospheres. Based on proper-motion measurements, the 3D kinematic of the star is investigated by means of numerical experiments.
Results. HD 271791 is found to be a massive (11 $M_{\odot}$), rapidly-rotating B-type star. Its chemical composition is found to be consistent with that of the sun. Its Galactic rest-frame velocity exceeds the Galactic escape velocity.
Conclusions. According to its space velocity, HD 271791 qualifies as a hyper-velocity star. Its kinematic constrains the place of birth to the outer Galactic disc and rules out the Galactic centre. HD 271791 is also too young (<30 Myr) to have originated in the Galactic centre. This challenges the SMBH paradigm for the origin of hyper-velocity stars.

Key words. stars: individual: HD 271791 – stars: distances – stars: early-type – stars: atmospheres – Galaxy: center – Galaxy: halo

1. Introduction

Young, massive stars are usually found close to the Galactic plane, preferentially in open clusters and associations. Some of them, however, are observed at high Galactic latitudes far away from star-forming regions. Since no gas clouds are known in the halo that have a sufficient density to form massive stars, these stars must have formed in the Galactic disc, and afterwards migrated outwards ("run-away B stars"). They are thought to have been ejected from their place of birth and accelerated to high velocity by dynamical processes either during the initial dynamical relaxation of a star cluster (Poveda et al. 1967), or in binary interaction inside star clusters (Leonard & Duncan 1988), or by means of a binary supernova explosion (Blaauw 1961).

HD 271791, which is also known as OM 88, is a well-known, apparently-normal, B-type star at high Galactic latitude ($l = 276.7°$, $b = -29.6°$). Kilkenny & Stone (1988) classified its spectrum as B2–3 III and derived its atmospheric parameters using Strömgren photometry and Balmer-line-profile fits (Hγ and Hδ) to be $T_{\rm eff} = 18\,000 \pm 1000$ K, and $\log g = 3.0 \pm 0.25$. A high projected rotational velocity of 170 ± 50 km s^{-1} was derived and the helium line-strengths were regarded as normal, although Kilkenny & Stone (1988) noted that the star may possibly be helium-rich. Because of its large distance from the Galactic plane ($z = 7.4$ kpc), HD 271791 was regarded as a run-away B-star. HD 271791 stands out because of its very high heliocentric radial velocity of 442 km s^{-1} (Kilkenny & Muller 1989).

In view of the discovery of so-called hyper-velocity stars (HVS), it is tempting to revisit HD 271791. HVSs move so rapidly that they are unbound to the Galaxy. The first HVSs were discovered serendipitously (Brown et al. 2005; Hirsch et al. 2005; Edelmann et al. 2005). A systematic search led to the discovery of seven additional HVSs (see Brown et al. 2007). Hills (1988) predicted that the tidal disruption of a binary by a supermassive black hole (SMBH) could lead to the ejection of stars at velocities that exceed the escape velocity of the Galaxy. The Galactic centre (GC) is believed to be the place of origin of HVSs because it hosts a SMBH.

At $V = 12.258 \pm 0.014$ mag (Kilkenny 1995), HD 271791 is much brighter than any of the HVSs known and can therefore be studied in greater detail, even using small telescopes. The kinematic studies of HVSs had to rely on radial-velocity measurements only, because proper motions have not yet been measured for these stars. For HD 271791, however, proper-motion measurements are available from seven sources including the Hipparcos mission and a new determination presented here.

We obtained high-resolution spectra of excellent quality, which we analyse here using line-blanketed LTE model atmospheres to constrain precisely the nature of the star (Sect. 2). In Sect. 3, we derive its mass, distance, and evolutionary lifetime. In Sect. 4, we investigate the space motion of HD 271791 to constrain its place of origin.

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[*] Based on observations collected at the European Southern Observatory at La Silla, Chile, ESO proposal No. 073.D-0495(A).

Table 1. Summary of the observing dates, measured heliocentric radial velocities and χ^2-fit results of the atmospheric parameters (errors are statistical ones, only) for HD 271791.

Date	$v_{\rm rad}$ km s^{-1}	$T_{\rm eff}$ K	log g cgs	log ($n_{\rm He}/n_{\rm H}$)
2005/2/23	+439.3	17789 ± 199	3.04 ± 0.03	−0.81 ± 0.02
2005/2/24	+440.4	18009 ± 155	3.07 ± 0.02	−0.81 ± 0.01
2005/2/28	+440.0	17718 ± 170	3.03 ± 0.03	−0.82 ± 0.02
2005/3/01	+443.6	17733 ± 191	3.03 ± 0.03	−0.80 ± 0.02

2. Observations and spectral analysis

We observed HD 271791 in early 2005 at the European Southern Observatory (ESO) on La Silla, Chile, using the FEROS spectrograph mounted on the 2.2 m telescope. A nominal resolution of $\lambda/\Delta\lambda$ = 48 000 was used. Four spectra of HD 271791 were acquired with a wavelength coverage of 3700 Å to 9200 Å. The signal to-noise ratio S/N per pixel at Hβ ranges from 55 to 75 for individual spectra. Radial velocities were measured with the FITSB2 program (Napiwotzki et al. 2004). For all four spectra, we determined a constant heliocentric radial velocity of +441 ± 1 km s^{-1} (see Table 1), perfectly consistent with the result from Kilkenny & Muller (1989) of +442 km s^{-1}.

Using a χ^2 fit technique (Napiwotzki et al. 1999), the stellar atmospheric parameters (effective temperature $T_{\rm eff}$, surface gravity log g, and photospheric helium abundance) were determined simultaneously. Synthetic line profiles were calculated using a grid of fully metal line blanketed LTE model atmospheres (Heber et al. 2000) and Lemke's version of the LINFOR program (Lemke 1997) and were matched to all observed Balmer (H_β up to H_{11}) and He I line profiles. The models used were plane-parallel and chemically homogeneous and consisted of hydrogen, helium, and metals of solar abundances. Beforehand, all spectra were normalised, and the model spectra had been folded by the instrumental profile which were Gaussians of appropriate width.

From the distribution of results obtained for our four individual high-resolution spectra obtained (see Table 1), we determine the atmospheric parameters of HD 271791 to be $T_{\rm eff}$ = 17 810 K, log g = 3.04 (cgs). The errors given in Table 1 are statistical ones. Systematic errors are larger but difficult to estimate. We therefore adopt $\Delta T = \pm 1000$ K and $\Delta \log g = \pm 0.1$ dex. These atmospheric parameters place HD 271791 in the domain of B-type giants. We find the helium abundance to be marginally higher than solar. Using the coadded spectrum, the projected rotational velocity is determined by a χ^2 fit to all Balmer and He lines. The synthetic spectra were calculated from the final model and folded with rotational profiles for various values of $v \sin\ i$. The best matching fit was achieved using $v \sin\ i$ = 124 ± 2 km s^{-1} (3σ error).

Metal absorption-lines of the ions C II, N II, O I, O II, Ne I, Mg II, Al III, Si II, Si III, S II, and S III are clearly present in the FEROS spectra. However, all lines are broadened due to the strong rotation of HD 271791. This renders a quantitative abundance analysis difficult. Nevertheless, we compared synthetic spectra calculated using LTE model atmospheres with different metal contents, with the strongest lines with the coadded FEROS spectrum. From Fig. 1, one can see that the metal abundance pattern for HD 271791 is close to solar composition, to within a factor of two. Its strong rotation and normal abundances indicate that HD 271791 is indeed a young massive star.

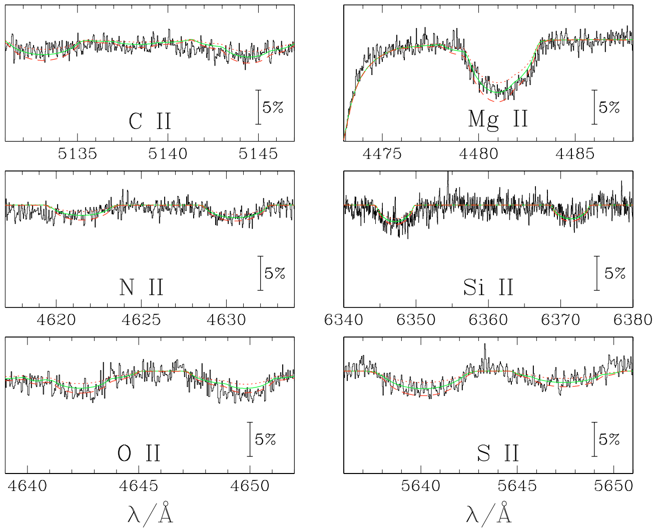

Fig. 1. Synthetic spectra overlayed to the coadded FEROS spectrum for solar (solid lines), half solar (dotted), and twice solar metal abundance (dashed). $T_{\rm eff}$ and log g were kept fixed. Displayed are the strongest lines in the spectrum representative of each element.

3. Mass, distance and evolutionary lifetime

After finding HD 271791 to be a massive B-type star of approximately solar metallicity, we estimate its mass and evolutionary lifetime by comparing its position in the ($T_{\rm eff}$, log g) diagram to evolutionary tracks (Meynet & Maeder 2003) for stars of solar metallicity and no rotation as illustrated in Fig. 2. More sophisticated stellar evolution models that consider rotation (Meynet & Maeder 2003) and magnetic fields (Maeder & Meynet 2005), are available. Due to its large projected rotation-velocity, which is at least 40% of the break-up velocity, the evolution of HD 271791 was probably influenced by rotation. Assuming conservation of angular momentum, its initial rotation velocity was at least 400 km s^{-1}. Therefore we show in addition evolutionary tracks that account for rotation (initially at 300 km s^{-1}). We determine a stellar mass of 11 ± 1 $M_\odot$ and an evolutionary lifetime of about 25 ± 5 Myr result.

HD 271791 was monitored by the All Sky Automated Survey (Pojmanski 2002) for about 2000 days; no light variations were obvious. The mean magnitude of V = 12.275 ± 0.057 mag from 285 individual measurements is consistent with that measured by Kilkenny (1995). Using the mass, effective temperature, gravity, apparent magnitude, and extinction (0.25 mag, Schlegel et al. 1998), we derive a distance using the method described by Ramspeck et al. (2001), of d = 21 ± 4 kpc.

4. Kinematics

Using the Galactic potential of Allen & Santillan (1991), we calculated orbits and reconstructed the path of the star back to the Galactic plane using the program of Odenkirchen & Brosche (1992). The distance of the Galactic centre from the Sun was adopted to be 8.0 kpc. In a numerical experiment, we treated the proper-motion components as free parameters and performed a search for a trajectory that leads from the Galactic centre to the star's present location on the sky, which produces vlaues of $\mu_\alpha \cos\delta$ = +1.25 mas yr^{-1} and μ_δ = +1.01 mas yr^{-1} and a time of flight of 75 Myr, which is much larger than the evolutionary lifetime.

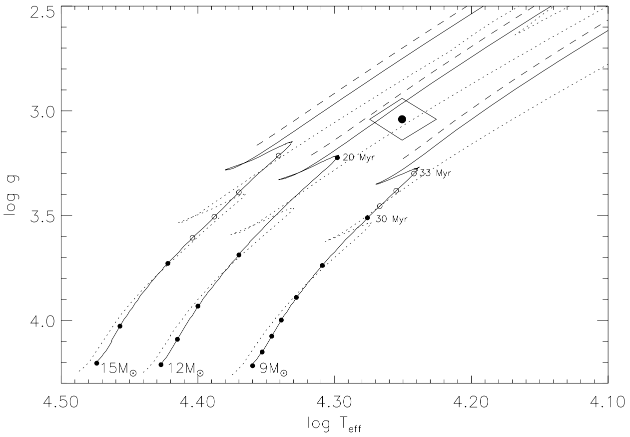

Fig. 2. Positions of HD 271791 in a ($T_{\rm eff}$, log g) diagram with evolutionary tracks calculated by (Meynet & Maeder 2003) to determine its mass and evolutionary lifetime. The full drawn line is for a star initially rotating at 300 km s^{-1}, while the dotted line depicts models that neglect rotation. The influence of magnetic fields is depicted by the dashed line estimated from Maeder & Meynet (2005). Time steps are marked by filled (5 Myr) and open (1 Myr) circles.

Table 2. Proper motions and corresponding Galactic rest-frame velocities $v_{\rm grf}$ assuming a distance of 20 kpc and a heliocentric radial velocity of 441 km s^{-1}. Catalogs used: original Hipparcos (ESA 1997), new Hipparcos (van Leeuwen 2007), ARIHIP (Wielen et al. 2001), Tycho-2 (Høg et al. 2000), ASCC (Kharchenko 2001), UCAC2 (Zacharias et al. 2004), USNO-B1 (Monet et al. 2003), ACT (Urban et al. 1998).

Catalog	$\mu_\alpha \cos\delta$ (mas yr^{-1})	μ_δ (mas yr^{-1})	$v_{\rm grf}$ (km s^{-1})
this paper	−1.0 ± 2.0	+6.2 ± 2.0	630
original Hipparcos	−1.26 ± 1.39	+9.50 ± 1.71	920
new Hipparcos	−1.50 ± 1.47	+6.89 ± 2.05	700
ARIHIP	−1.05 ± 1.24	+8.56 ± 1.43	860
UCAC2	−3.5 ± 1.6	+4.6 ± 1.1	640
TYC2	+0.1 ± 2.5	+6.5 ± 2.4	630
ASCC	−0.96 ± 1.82	+8.01 ± 2.16	780
USNO-B1	0	+6	600
ACT	−3.6	+2.1	530

We measured the proper motion using four epochs from the SuperCOSMOS Sky Surveys (Hambly et al. 2001), one from the 2MPSC (Cutri et al. 2003), and one from the AC2000 (Urban et al. 1998). Proper-motion values are listed in addition in eight catalogues (see Table 2). It is remarkable that the change from the original Hipparcos (ESA 1997) to the new Hipparcos reduction (van Leeuwen 2007) leads to a more consistent result compared with all others, which depend on the old (AC2000) epoch positions. Our result agrees well with the newly-reduced Hipparcos proper motion as well as with the ARIHIP, Tycho-2 and ASCC catalogs (see Fig. 3). The UCAC2 value deviates somewhat but is consistent with our measurement if the margins of error are taken into account. The quality of the USNO-B and ACT values are difficult to assess, since no error estimates are available. Most importantly, the proper motion required for the Galactic centre (see above) is inconsistent with all proper-motion measurements. Hence, we can exclude the Galactic centre as the place of birth both using the proper-motion measurement in addition to the exceedingly long time of flight.

Using the available constraints on its proper motion, we calculated trajectories for HD 271791 back to the Galactic plane to identify its place of origin. Proper motions were varied within their margins of error. We assumed the longest possible lifetime (30 Myr) because this provides the largest coverage of the Galactic disc. Figure 4 displays those regions of the Galactic disc from which HD 271791 can have reached its present position, as constrained by our proper motion measurement (red) and by the UCAC2 value (blue). For simplicity, the Galactic disc is assumed to be circular with a radius equal to twice the distance to the Galactic centre (16 kpc). As can be seen these areas lie close to the outer edge of the Galactic disc, far from the Galactic centre. Since the time of flight must not exceed the stellar lifetime, which is less than 30 Myr, we are able to constrain further the place of birth (see Fig. 4). Hence, we should look for the place of birth of HD 271791 in the outskirts of the Galactic disc, and not in the Galactic centre.

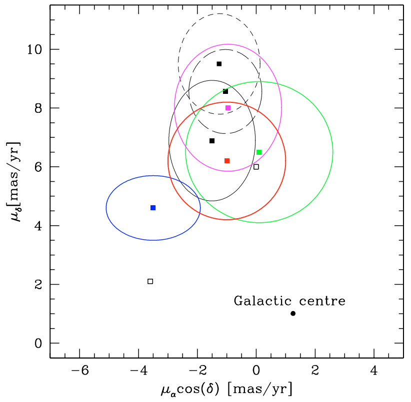

Fig. 3. Proper motions with error ellipses from different sources (see Table 2): our results (red), new Hipparcos (black), original Hipparcos (short dashed black), ARIHIP (long dashed black), UCAC2 (blue), Tycho-2 (green), ACSS (cyan). USNO-B and ACT proper motions are displayed as open squares. The proper motions required for the star to originate in the Galactic centre are shown by a filled circle.

Table 2 lists the Galactic rest-frame velocity that range from 530 km s^{-1} to 920 km s^{-1}. The escape velocity at the position of HD 271791 is about 430 km s^{-1} (Allen & Santillan 1991). The Galactic rest-frame velocity for HD 271791 is far higher than this value, which implies an unbound orbit. Hence, HD 271791 should be classified as a hyper-velocity star that will escape from the Galaxy.

5. Discussion and conclusions

We confirm the high heliocentric velocity found by Kilkenny & Muller (1989) and derive +441 ± 1 km s^{-1} using our high-resolution spectra. We present a detailed spectroscopic analysis and determine the atmospheric parameters of HD 271791 from the Balmer and helium lines to be $T_{\rm eff}$ = 17 800 ± 1000 K and log g = 3.04 ± 0.1. The star is rapidly rotating at $v \sin i$ = 124 ± 2 km s^{-1}. These results are in excellent agreement with those of Kilkenny & Stone (1988). An LTE analysis of the strongest metal lines indicates close to solar abundances. Accordingly, HD 271791 is a massive B giant of M = 11 ± 1 $M_\odot$ and an age of 25 ± 5 Myr.

We measure the proper motion and find the result to be consistent with measurements by the Hipparcos and Tycho space missions in additon to four independent ground based measurements. Using our kinematical experiments, we identify a region of the outer Galactic disc from which HD 271791 could have reached its present location within its lifetime, in accordance with the proper-motion measurements. The time of flight from

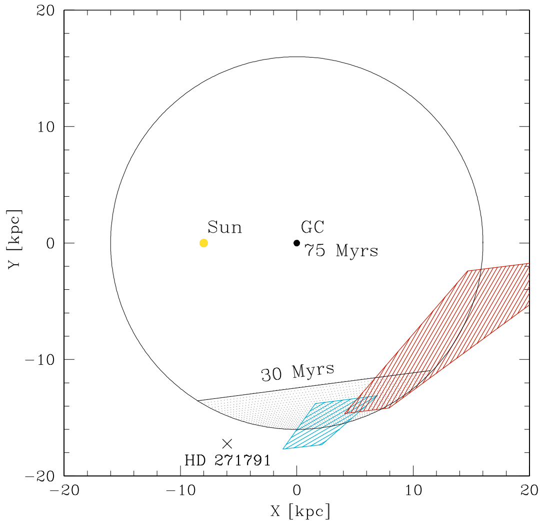

Fig. 4. Regions of origin for HD 271791 in the Galactic plane (sketched as a circle of 16 kpc radius around the GC) calculated by varying the proper-motion components within their measurement errors. The position of HD 271791 projected to the Galactic plane is marked. The star is actually 9.9 kpc below it. The red area is derived from our proper-motion measurement, whereas the blue area follows if proper motions from the UCAC2 catalog are used. The black line marks the time of flight of 30 Myr. Accordingly the place of birth of HD 271791 would be restricted to the small red and blue regions below that line (see text).

the Galactic centre would be three times as long as the evolutionary lifetime. This could be reconciled if HD 271791 is a blue straggler formed by a merger of two lower mass stars (see Perets 2008, and references therein). However, if HD 271791 did originate from the Galactic centre, its proper motion would be inconsistent with all measured values. This rules out the Galactic centre as the place of birth even if HD 271791 were a blue-straggler star.

The Galactic rest-frame velocity of HD 271791 is found to be larger than the local escape velocity. Hence HD 271791 qualifies as an unbound hyper-velocity star.

Having excluded the Galactic centre as the place of origin, the SMBH slingshot scenario or other ejection models (e.g. Baumgardt et al. 2006) invoking a SMBH are ruled out. An additional physical mechanism capable of accelerating a massive star to a space velocity of 500 km s^{-1} or more has to be envisaged. HD 271791 is the second star that challenges the SMBH paradigm. Edelmann et al. (2005) and Przybilla et al. (2008) found the hyper-velocity star HE 0437−5439 to be too young to originate in the Galactic centre. Moreover, its chemical composition differs significantly from that of the Galactic centre. Przybilla et al. (2008) found the abundance pattern to be consistent with that of the LMC as well as with that of the outer Galactic disc. An origin in the latter, however, was considered unlikely, because the time of flight would be too long. Therefore, Przybilla et al. (2008) concluded that the star originates in the LMC. Bonanos et al. (2008) came to the same conclusion based solely on an abundance analysis.

The projected rotation is within the average range measured for B2−3 III type stars (see Table 2 of Abt et al. 2002). Because of tidal locking, the rotation of the star ejected by binary disruption should be lower than for normal B stars. (Hansen 2007). Przybilla et al. (2008) suggested two alternative scenarios proposed in the literature recently: I) A close encounter of a binary with an intermediate-mass black hole (IMBH) more massive than $10^3\ M_\odot$ proposed as a viable ejection mechanism by Gualandris & Portegies Zwart (2007); and II) dynamical ejection by interaction of massive binaries in the cores of dense clusters (Gvaramadze et al. 2008). These scenarios should be investigated further to model the origin of HD 271791.

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