A&A 480, L37–L40 (2008)
DOI: 10.1051/0004-6361:200809391

Astronomy & Astrophysics

Letter to the Editor

LMC origin of the hyper-velocity star HE 0437−5439[⋆]

Beyond the supermassive black hole paradigm

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Received 12 January 2008 / Accepted 28 January 2008

ABSTRACT

Context. Hyper-velocity stars move so fast that only a supermassive black hole (SMBH) seems to be capable of accelerating them. Hence the Galactic centre (GC) is the only place suggested as their origin. We discovered earlier that the object HE 0437−5439 is a hyper-velocity star. However, this early B-type star is too short-lived to have reached its current position in the Galactic halo if ejected from the GC, except if it is a blue straggler. Its proximity to the Large Magellanic Cloud (LMC) suggests an origin in this galaxy.
Aims. The chemical signatures of stars at the GC are significantly different from those in the LMC. As a result, an accurate determination of the abundance pattern of HE 0437−5439 will yield a new tight constraint on the place of birth of this hyper-velocity star.
Methods. High-resolution spectra obtained with UVES on the VLT were analysed using state-of-the-art NLTE modelling techniques.
Results. We determined abundances of individual elements to very high accuracy in HE 0437−5439, as well as in two reference stars from the LMC and the solar neighbourhood. The abundance pattern is not consistent at all with that observed in stars near the GC, ruling out an origin from the GC. However, there is a high degree of consistency with the LMC abundance pattern. Our abundance results cannot rule out an origin in the outskirts of the Galactic disk. However, we find the lifetime of HE 0437−5439 to be more than three times shorter than the time of flight to the edge of the disk, rendering a Galactic origin unlikely.
Conclusions. Only one SMBH is known to be present in the Galaxy and none in the LMC. Hence the exclusion of an GC origin challenges the SMBH paradigm. We conclude that there must be other mechanism(s) than the SMBH that accelerate stars to hyper-velocity speed. We draw attention to dynamical ejection from dense massive clusters, as recently proposed.

Key words. Galaxy: halo – galaxies: Magellanic Clouds – stars: abundances – stars: distances – stars: early-type – stars: individual: HE 0437−5439

1. Introduction

Stars moving faster than the Galactic escape velocity were first predicted by Hills (1988). The first such hyper-velocity stars (HVSs) have only recently been discovered serendipitously (Brown et al. 2005; Hirsch et al. 2005; Edelmann et al. 2005, E05: HE 0437−5439 at 723 km s^{-1} heliocentric radial velocity). A systematic search for such objects has resulted in the discovery of seven additional HVS until now (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 with velocities exceeding the escape velocity of our Galaxy. The Galactic centre (GC) is the suspected place of origin of the HVSs, as it hosts an SMBH. Both the moderate rotational velocity ($v \sin i = 54$ km s^{-1}) and the chemical composition (consistent with solar abundances within a factor of a few from an LTE analysis of a spectrum with $S/N \approx 5$) were considered evidence of the main sequence nature of HE 0437−5439 (E05). This put the star at a distance of ≈60 kpc.

Numerical kinematical experiments have been carried out to trace the trajectory of HE 0437−5439 from the GC to its present location in the Galactic halo. However, its travel time (100 Myr) was found to be much longer than its main sequence lifetime (≈25–35 Myrs), rendering a GC origin unlikely, though it would be possible if HE 0437−5439 were a blue straggler star. Alternatively, the star could have originated in the Large Magellanic Cloud (LMC) because it is much closer to this galaxy (18 kpc) than to the GC.

An accurate determination of its elemental abundance pattern should allow us to distinguish between an origin in the LMC or in the GC because their chemical compositions differ considerably. HE 0437−5439 is by far the brightest HVS known ($V = 16.36$, Bonanos & López-Morales 2008), making it the best choice for a detailed analysis. With this in mind, we obtained high-resolution, high S/N spectra of HE 0437−5439 at the ESO VLT with UVES and performed a quantitative spectral analysis using state-of-the-art non-LTE modelling techniques.

2. Observations and quantitative non-LTE analysis

Nine spectra of HE 0437−5439 with a total integration time of ∼4 h were obtained on January 12, 2006, covering the range of 3750 to 4950 Å and 5700 to 9400 Å at a resolving power of $R \approx 35\,000$. The data reduction followed procedures described by Koester et al. (2001). We took a spectrum of the DC white dwarf WD0123−262, such that a reliable continuum normalisation in the blue could be achieved, a region containing many broad Balmer lines. Moreover, the method reliably removes fringes

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[⋆] Based on observations collected at the European Southern Observatory, Paranal, Chile (DDT proposal 276.B-5024).

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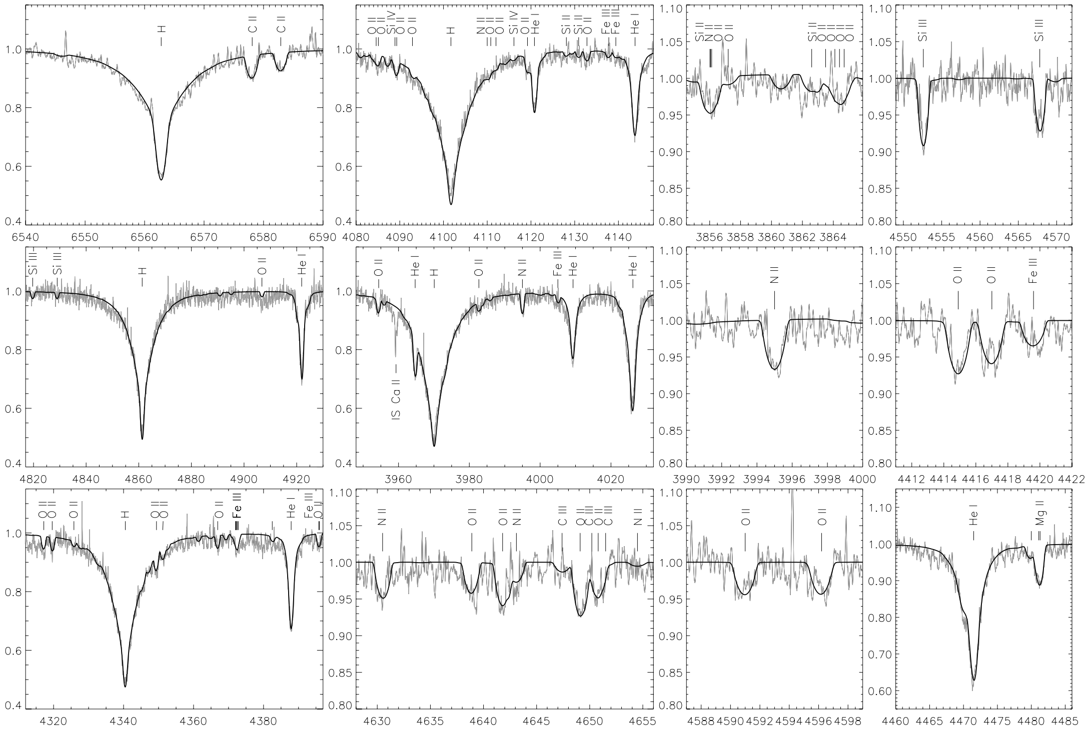

Fig. 1. Comparison of spectrum synthesis for HE 0437−5439 (full line) with observations (grey). The main spectral features are identified. Weak interstellar Ca II H & K lines are due to the Galactic foreground, indicating only a small amount of reddening.

in the red, improving considerably on the standard UVES data-reduction pipeline. A peak S/N of ≈80 per resolution element is measured for the coadded spectrum in the blue.

Two comparison stars with similar atmospheric parameters were considered: the LMC object NGC 2004-D15 (Korn et al. 2002, K02) and HR 3468 in the solar neighbourhood (Nieva & Przybilla 2008, NP08). The same data reduction procedures as were used for HE 0437−5439 were applied to the UVES spectrum of NGC 2004-D15, obtained from the ESO archive. A comparison with the LMC star allowed for a consistency test with the LMC baseline abundances determined from main sequence B-type stars in previous studies (e.g. K02; Trundle et al. 2007).

The quantitative analysis of the 3 stars was carried out following the methodology discussed by Nieva & Przybilla (2007) and NP08. In brief, non-LTE line-formation calculations were performed on the basis of line-blanketed model atmospheres, using updated versions of DETAIL and SURFACE (Giddings 1981; Butler & Giddings 1985). State-of-the-art model atoms were employed – H: Przybilla & Butler (2004); He I: Przybilla (2005); C II/III: Nieva & Przybilla (2006), NP08; N II: Przybilla & Butler (2001); O I: Przybilla et al. (2000); Mg II: Przybilla et al. (2001); Fe III as adopted by Morel et al. (2007); an updated model for O II, originally by Becker & Butler (1988). Our extensions and improvements of the original Si II/III/IV model atom from Becker & Butler (1990) were crucial for our analysis as this ionisation equilibrium is our primary temperature indicator. Tests with high-S/N spectra of Galactic stars showed that the models allow the observed spectra for these elements to be reproduced with high accuracy, hence atmospheric parameters and elemental abundances to be determined with small uncertainties.

The atmospheric parameters ($T_{\rm eff}$, log g) were determined from metal ionisation equilibria (mainly Si II/III/IV, but also O I/II and C II/III, where available) and the Stark-broadened Balmer lines. Microturbulence ξ was derived in the standard way by demanding that the line equivalent widths within an ion be independent of abundance. Elemental abundances were determined from χ^2-minimisation of fits to individual metal line profiles.

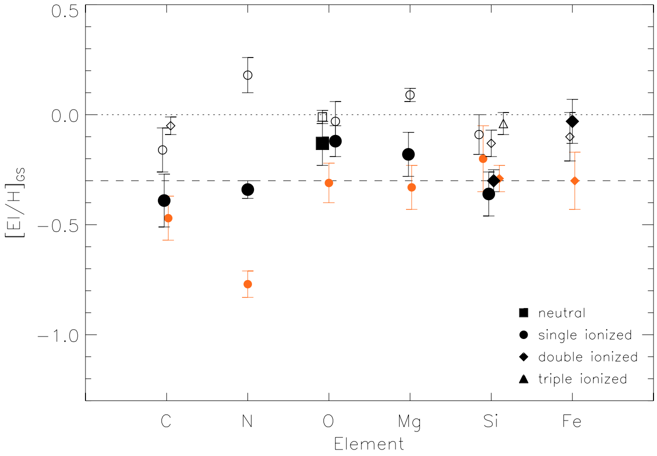

Fig. 2. Metal abundances in the three programme stars (Table 1), relative to the solar standard (Grevesse & Sauval 1998): HE 0437−5439 (black symbols), NGC 2004-D15 (red symbols), and HR 3468 (open symbols). Ionic species are encoded according to the legend. Solar and half-solar values are indicated by dotted and dashed lines, respectively.

Basic stellar parameters and metal abundances for the programme stars are listed in Table 1. Masses and evolutionary lifetimes were determined by comparison with evolutionary tracks from Schaller et al. (1992) and Schaerer et al. (1993) for solar and LMC metallicity, respectively. Note that the actual metallicity of HE 0437−5439 is $Z \approx 0.013$, which gives a significantly lower age (18 Myr) than found by E05 (25–35 Myr). The corresponding distance to HE 0437−5439 is 61 ± 9 kpc, in perfect agreement with E05.

The uncertainties in the atmospheric parameters were constrained by the quality of the simultaneous fits to all diagnostic

Table 1. Stellar parameters of the programme stars & elemental abundances $\varepsilon(X) = \log(X/\mathrm{H}) + 12$ (number of lines analysed in parenthesis).

	HE 0437−5439	NGC2004-D15	HR 3468
$T_{\rm eff}$ (K)	23 000 ± 1000	21 500 ± 1000	22 900 ± 400
$\log g$ (cgs)	3.95 ± 0.10	3.70 ± 0.10	3.60 ± 0.05
ξ (km s^{-1})	1 ± 1	1 ± 1	5 ± 1
$\upsilon \sin i$ (km s^{-1})	55 ± 2	48 ± 3	11 ± 2
$M/M_\odot$	9.1 ± 0.8	9.5 ± 0.8	11.6 ± 0.5
Age (Myr)	18 ± 3	23 ± 1	14.5 ± 0.5
ε(C II)	8.13 ± 0.12 (3)	8.05 ± 0.10 (1)	8.36 ± 0.10 (17)
ε(C III)	…	…	8.47 ± 0.04 (2)
ε(N II)	7.58 ± 0.04 (7)	7.15 ± 0.06 (4)	8.10 ± 0.08 (54)
ε(O I)	8.70 ± 0.10 (1)	…	8.82 ± 0.02 (4)
ε(O II)	8.71 ± 0.07 (40)	8.52 ± 0.09 (31)	8.80 ± 0.09 (45)
ε(Mg II)	7.40 ± 0.10 (1)	7.25 ± 0.10 (1)	7.67 ± 0.03 (2)
ε(Si II)	7.20 ± 0.10 (3)	7.37 ± 0.15 (3)	7.47 ± 0.09 (7)
ε(Si III)	7.26 ± 0.05 (4)	7.30 ± 0.12 (3)	7.43 ± 0.06 (5)
ε(Si IV)	…	…	7.52 ± 0.05 (2)
ε(Fe III)	7.47 ± 0.10 (3)	7.20 ± 0.13 (3)	7.40 ± 0.11 (37)

indicators: all hydrogen and helium lines and multiple metal ionisation equilibria. Such a good match has never before been reported in B-star analyses. The helium abundance in the three stars was found to be consistent with the solar value. Standard deviations σ for metal abundances were calculated from the individual line abundances in an ion. The derived uncertainties are extremely low for B-stars analyses. We adopted $\sigma = 0.10$ dex for ions with only one observed line. In addition, systematic errors need to be considered because of uncertainties in the stellar parameters, atomic data, and the quality of the spectra. In fact, the precision of the analysis is limited mostly by the noise level of the spectra. A laborious procedure for minimising systematics has been developed by NP08, which allows us to estimate the systematic uncertainties in elemental abundances to be 0.10 dex for HR 3468 and 0.15 dex for the other two stars. This significant improvement over previous B star analyses can only be obtained when major sources of systematic errors are eliminated (NP08). The resulting synthetic spectrum is compared with observation of HE 0437−5439 in Fig. 1, for many strategic spectral regions. The match between theory and observation is excellent within the S/N limitations. The fits obtained for the other two stars are of similar quality.

Abundance patterns for the three programme stars are visualised in Fig. 2, relative to the solar standard (Grevesse & Sauval 1998)[1]. Note the small line-to-line-scatter and the agreement of abundances for different ions of the elements, *simultaneously* for all ionisation equilibria. This can only be achieved when the stellar parameters are constrained well and highly reliable model atoms are employed in the non-LTE calculations. Metal ionisation equilibria show a much higher sensitivity to parameter variations than the H/He lines alone. This explains part of the parameter offset with regard to the LTE analysis of HE 0437−5439 by E05. We derived a somewhat lower $T_{\rm eff}$ and $\log g$ for NGC 2004-D15 than K02, though within the mutual uncertainties.

Elemental abundances in NGC 2004-D15 are about half solar, except for nitrogen, which generally agrees with the baseline metallicity derived in previous studies of early-type stars in the LMC. Nitrogen is known to have a low pristine abundance in the LMC (e.g. K02). We thus confirm that NGC 2004-D15 is essentially unaffected by mixing with CN-cycled material. Abundances in the Galactic star HR 3468 are near-solar, except for enriched N. The abundances in HE 0437−5439 tend to be intermediate, with a solar N/C ratio.

3. Constraints on the origin of HE 0437−5439 from its chemical signature

We now compare the abundance pattern of HE 0437−5439 to the chemical signatures of the two suggested places of origin, the Galactic centre, on the one hand, and the LMC, on the other.

The Galactic centre. A comparison of the abundance pattern of HE 0437−5439 to that of a sample of stars near the GC (Cunha et al. 2007; Najarro et al. 2008) is depicted in Fig. 3 (upper panel), for average values over all ions of an element. The sum of carbon and nitrogen is considered to remove signatures of mixing with nuclear-processed matter from the individual abundances (as catalysts, their total number is conserved in the CN-cycle). The α-elements oxygen, magnesium, silicon, and C + N are super-solar and enhanced relative to iron in the GC sample. In HE 0437−5439, however, they are subsolar and depleted compared to iron. This rules out HE 0437−5439 as of GC origin.

LMC. A comparison of the abundance pattern in HE 0437−5439 with the LMC reference star is made in the middle panel of Fig. 3. Both patterns are very similar since all error bars overlap. There is a tendency for the abundances of HE 0437−5439 to be slightly higher than in NGC 2004-D15 (from 0.04 dex for C + N to 0.27 dex for Fe, with an exception in Si). These abundances are fully consistent with today's knowledge of the abundance scatter within the LMC (e.g. Luck & Lambert 1992; Hill et al. 1995), consistent with the origin of HE 0437−5439 being in this galaxy.

Galactic disk. We are reluctant to accept the LMC origin before having discussed other options for a Galactic disk origin. From Fig. 3 (lower panel) it can be seen that HE 0437−5439 and the solar neighbourhood star HR 3468 have similar abundances within error limits, when compared on an element-to-element basis. However, there is a tendency for all elements except iron to be less abundant in HE 0437−5439, by 0.09 dex (O) to 0.27 dex (Mg). Such an abundance pattern would restrict the place of birth of HE 0437−5439 to outside the solar circle because of the Galactic abundance gradient. Consequently, we cannot rule out an origin in the outskirts of the Galactic disk from the chemical signature alone.

4. Kinematics revisited

Edelmann et al. (2005) suggested that the LMC is the place of origin solely because of the discrepancy between evolutionary lifetime and time of flight. We have recalculated the kinematics on the basis of the significantly reduced age of HE 0437−5439, following the procedure of E05. Such an estimate also has to account for the large space-motion of the LMC (e.g. Piatek et al. 2008) of about 500 pc/Myr in direction east-northeast. The total distance to travel by HE 0437−543 after ejection ∼18 Myr ago is therefore $\sim 19^{+7}_{-3}$ kpc, meaning the total ejection velocity should amount to ∼1000 km s^{-1}, if originating in the kinematic centre of the LMC. When considering the extension of the LMC, ejection velocities may vary by ∼100 km s^{-1}.

Flight times from the outer Galactic disk to the current position of HE 0437−5439 are depicted in Fig. 4 of E05, who

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[1] Similar conclusions are drawn in the following if the revised solar abundances of Grevesse et al. (2007) are used.

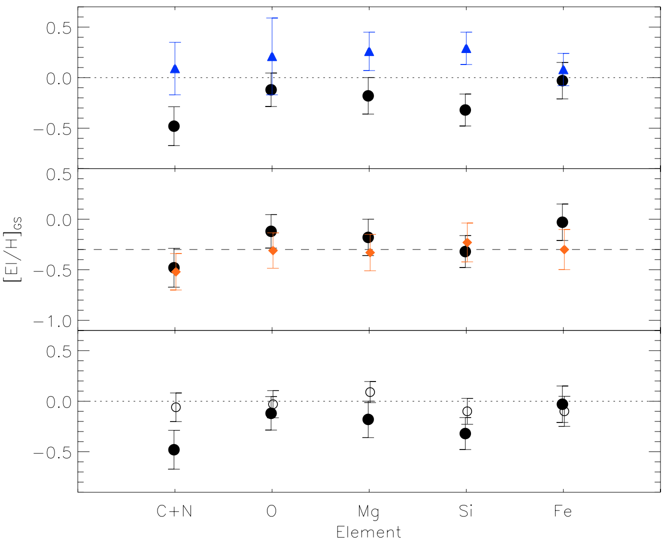

Fig. 3. Comparison of metal abundances in HE 0437−5439 (black dots) with a sample of stars close to the GC (blue triangles) in the upper panel, the LMC reference star NGC 2004-D15 (red diamonds) in the middle panel, and the solar neighbourhood reference star HR 3468 (circles) in the lower panel. Error bars account for statistic and systematic uncertainties.

suggested that the age discrepancy could be overcome if the HVS were a blue straggler formed by a merger of less massive stars. Our revised mass would require a merger of two $\sim 5\,M_\odot$ stars to form a blue straggler with the observed parameters for HE 0437−5439. Their individual lifetimes are about the same as the time of flight, rendering an origin in the Galaxy very unlikely.

5. Conclusion

We performed a quantitative spectral analysis of the HVS HE 0437−3954 and reference objects in the LMC and the solar neighbourhood. The state-of-the-art non-LTE modelling techniques allowed precise elemental abundances to be obtained.

From the results of the spectroscopic analysis, we can rule out a GC origin for HE 0437−3954 because its abundance pattern indicates neither high metallicity nor α-enrichment. On the other hand, a high degree of consistency with the LMC pattern is found when considering an abundance scatter within the LMC[2]. The observed abundance pattern could also be consistent with an origin on the outskirts of the Galactic disk, in the case of HE 0437−3954 being a blue straggler. However, a comparison of the time-of-flight with the lifetime of the blue straggler practically rules out this scenario, making it unlikely that HE 0437−3954 has a Galactic origin.

Edelmann et al. (2005) suggested that HE 0437−3954 was ejected from the LMC. Our spectroscopic analysis lends strong support to this scenario. The abundance pattern is consistent with that of our LMC reference star. An ejection velocity of about $1000\,\mathrm{km\,s^{-1}}$ is required for the star to have reached its position from the LMC. Accurate proper motion measurements are needed to finally confirm the LMC origin.

Because no SMBH is known to exist in the LMC, the SMBH slingshot scenario or other ejection models (e.g. Baumgardt et al. 2006) invoking an SMBH are ruled out. There must therefore be an additional physical mechanism capable of accelerating a massive star to a space velocity of $1000\,\mathrm{km\,s^{-1}}$.

Two such alternative scenarios have been proposed. I) A close encounter of a binary with an intermediate-mass black hole (IMBH) more massive than $10^3\,M_\odot$ has been proposed as a viable ejection mechanism by Gualandris & Portegies Zwart (2007), who suggest that the populous dense clusters NGC 2004 or NGC 2100 in the LMC could harbour such an IMBH. II) Dynamical ejection by interaction of massive binaries in the cores of dense clusters is plausible (Gvaramadze et al. 2008). This process is more likely to occur in the LMC than in the Galaxy because the LMC hosts a significant number of sufficiently massive and dense clusters. From the list of Mackey & Gilmore (2003), eight young clusters can be identified to have the right age to qualify as candidate places of birth for HE 0437−3954. Primary candidates are NGC 2100 and NGC 2004, followed by NGC 1850 and NGC 1847.

In consequence, hyper-velocity stars are not all that simple probes for the shape of the Galactic halo as suggested e.g. by Gnedin et al. (2005). The fundamental assumption that the GC is the exclusive origin of HVSs has to be dropped, as acceleration may also occur in clusters throughout the Galactic disk.

Acknowledgements. We thank the Director General of ESO for making this study possible by granting director's discretionary time and the staff of the ESO Paranal observatory for their valuable support. M. F. N. and M. F. gratefully acknowledge financial support by the Deutsche Forschungsgemeinschaft (grants HE 1356/45-1 and PR 685/3-1).

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[2] More comprehensive investigations than presently available, using improved analysis techniques on larger samples of young stars covering the entire region of the LMC, are needed to draw definite conclusions on the degree of chemical (in)homogeneity in that galaxy.