Astronomy
&
Astrophysics

US 708 – an unbound hyper-velocity subluminous O star

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ABSTRACT

We report the discovery of an unbound hyper-velocity star, US 708, in the Milky Way halo, with a heliocentric radial velocity of $+708 \pm 15\,\mathrm{km\,s^{-1}}$. A quantitative NLTE model atmosphere analysis of optical spectra obtained with *LRIS* at the Keck I telescope shows that US 708 is an extremely helium-rich ($N_{\mathrm{He}}/N_{\mathrm{H}} = 10$) subluminous O type star with $T_{\mathrm{eff}} = 44\,500$ K, $\log g = 5.23$ at a distance of 19 kpc. Its Galactic rest frame velocity is at least $751\,\mathrm{km\,s^{-1}}$, much higher than the local Galactic escape velocity indicating that the star is unbound to the Galaxy. It has been suggested that such hyper-velocity stars can be formed by the tidal disruption of a binary through interaction with the super-massive black hole (SMBH) at the Galactic centre (GC). Numerical kinematical experiments are carried out to reconstruct the path from the GC. US 708 needs about 32 Myrs to travel from the GC to its present position, less than its evolutionary lifetime. Its predicted proper motion $\mu_\alpha \cos \delta = -2.3\,\mathrm{mas\,yr^{-1}}$ and $\mu_\delta = -2.4\,\mathrm{mas\,yr^{-1}}$ should be measurable by future space missions. We conjecture that US 708 is formed by the merger of two helium white dwarfs in a close binary induced by the interaction with the SMBH in the GC and then escaped.

Key words. stars: individual: US 708 – stars: subdwarfs – stars: early-type – stars: atmospheres – Galaxy: halo – Galaxy: centre

1. Introduction

High velocity O and B type stars at high Galactic latitudes have been known since decades (Blaauw 1961). These are often called *runaway stars*, as they are moving away at high velocities from their place of birth in the Galactic plane. None of the runaway O and B stars were known to have velocities so high as to exceed the Galactic escape velocity and, therefore, leave the Galaxy. Recently, Brown et al. (2005) discovered a so-called hyper-velocity star (HVS), the faint B-type star SDSS J090745.0+024507 ($B = 19.8$), in the Sloan Digital Sky Survey (*SDSS*) with a heliocentric radial velocity of $853\,\mathrm{km\,s^{-1}}$ unbound to the Galaxy. Photometric investigations showed it to be a slowly pulsating B-type main sequence star (Fuentes et al. 2005). Soon thereafter, the 16th magnitude star HE 0437-5439 was found to be a main sequence B star at a radial velocity of $723\,\mathrm{km\,s^{-1}}$, which exceeds the Galactic escape velocity (Edelmann et al. 2005). Brown et al. (2005) conclude that their HVS was ejected from the Galactic centre (GC) because only a massive black hole could plausibly accelerate the 3 $M_\odot$ main sequence B star to such an extreme velocity. Moreover, their star's lifetime, radial velocity vector, and solar metalicity were consistent with a GC origin. A proper motion of $\approx 2\,\mathrm{mas\,yr^{-1}}$ is necessary for the star to have come within a few parsec of the GC (Gualandris et al. 2005), with the intrinsic proper motion being a few tenth of a $\mathrm{mas\,yr^{-1}}$ (Gnedin et al. 2005). HE 0437-5439, however, cannot originate from the Galactic

centre unless it is a blue straggler, because the evolutionary life time is found to be much shorter than the time of flight. Edelmann et al. (2005) pointed out that HE 0437-5439 may have been ejected from the Large Magellanic Cloud (LMC) instead, because it is much closer to the LMC than to the GC and the required time of flight from the centre of the LMC to its present position is sufficiently short.

Hills (1988) predicted that velocities even in excess of $1000\,\mathrm{km\,s^{-1}}$ can be gained by the disruption of a binary through tidal interaction with the super-massive black hole (SMBH) in the GC (Schödel et al. 2003; Ghez et al. 2005). Therefore a HVS could be ejected from the GC by tidal breakup of a binary. If HE 0437-5439 originates from the LMC centre, its existence may be evidence for a central massive black hole in the LMC (Edelmann et al. 2005)

Here we report the discovery of a third HVS, US 708, with a heliocentric radial velocity of $708 \pm 15\,\mathrm{km\,s^{-1}}$. Unlike the two known HVSs, US 708 is an evolved low mass star of spectral type sdO.

2. Observations

US 708 was discovered by Usher et al. (1982) as a faint blue object ($B = 18.5$) at high Galactic latitudes ($l = 175.99°$, $b = +47.05°$), but no follow-up observations have been published. The object was rediscovered by the *SDSS* as
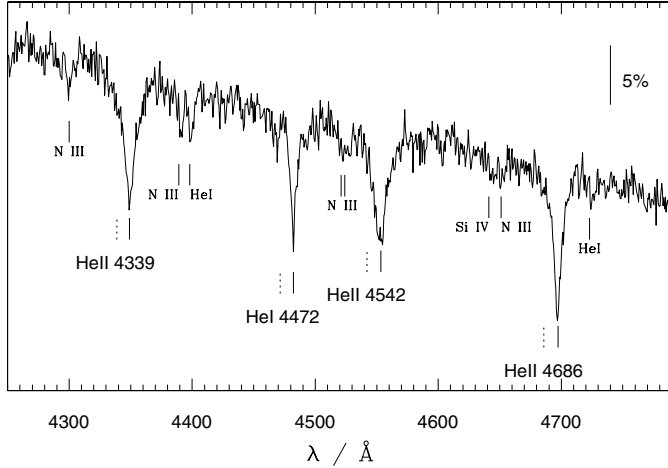
Fig. 1. Section of the spectrum of US 708. Rest-wavelengths of the strongest lines are marked as dashed lines. Note the large redshifts.

Fig. 2. Fit of line profiles for US 708. The observed spectrum is plotted as a histogram, the synthetic spectrum is the solid line.

SDSS J093320.86+441705.4 and *ugriz* magnitudes of 18.35, 18.75, 19.30, 19.67, 20.05, respectively, were measured.

We initiated a search for subluminous O stars in the *SDSS* spectral database by selecting all objects within a colour range of $(u' - g') < 0.2$ and $(g' - r') < 0.1$. By visual inspection we classified ≈ 100 of them as subluminous O stars according to their spectra showing lines of neutral as well as ionized helium. While most stars of the sample have small radial velocities, the spectrum of one star, US 708, is redshifted by about 10 Å.

US 708 belongs to the HesdO subclass (see, Ströer et al. 2005) because no contribution of hydrogen Balmer blends to the He II Pickering lines is visible to the eye.

However, we cannot exclude that the unusually high redshift may be an artifact. For verification we used the Keck I telescope with *LRIS* (Low Resolution Imaging Spectrometer). The setup used was the 1''5 wide long slit with the 600/4000 grism for the blue arm (exposure time 900s). This yields a resolution of 5 Å – a lower resolution than *SDSS*, but with sufficiently high S/N to measure a reliable radial velocity. The spectrum was calibrated using Hg, Cd and Zn lamps for the wavelength range 3900 Å to 5000 Å and shows ten helium lines, out of which six (He I 4472 and 4922 Å; He II 4339, 4542, 4686 and 4859 Å) were found to be useful to measure the radial velocity. A section of the spectrum is displayed in Fig. 1. The resulting heliocentric radial velocity is $708 \pm 15 \, \mathrm{km \, s^{-1}}$, to our knowledge the third largest measured for any Galactic star.

3. Atmospheric parameters and distance

A quantitative spectral analysis was performed using an extensive grid of NLTE model atmospheres calculated using the latest version of the PRO2 code (Werner & Dreizler 1999) that employs a new temperature correction technique (Dreizler 2003). A new detailed model atom for helium appropriate for the sdO temperature regime was constructed (Ströer et al. 2005). The model composition is hydrogen and helium only, line blanketing effects of H and He lines are accounted for. To determine the stellar parameters T_{eff}, $\log g$ and $\log(N_{\mathrm{He}}/N_{\mathrm{H}})$, we used the program *FITPROF 2.2* (Napiwotzki et al. 1999),
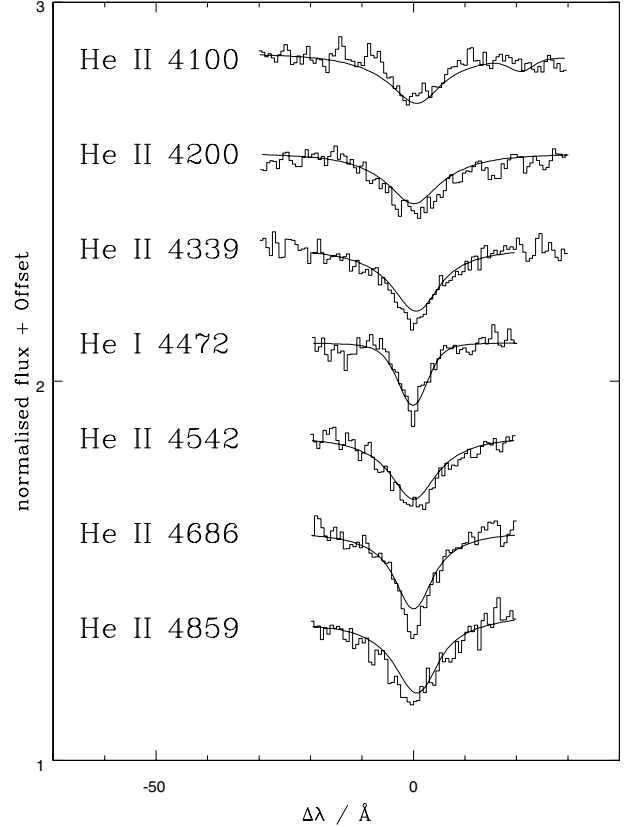
which uses a χ^2 fit technique to determine all three atmospheric parameters simultaneously by matching the synthetic spectra to the observation. Beforehand all spectra were normalized and the model spectra were folded with the instrumental profile (Gaussian with appropriate width).

The following atmospheric parameters result: $T_{\mathrm{eff}} = 45\,561 \pm 675$ K, $\log g = 5.23 \pm 0.12$, $\log(N_{\mathrm{He}}/N_{\mathrm{H}}) = 0.99 \pm 0.18$. Note that the errors are statistical only, The line profile fit is displayed in Fig. 2. Overall the fit is quite acceptable, although some line cores, He II 4686 Å in particular), are not well reproduced (see Fig. 2). Whether this is due shortcoming in the atmospheric models (e.g. metal line blanketing) or an instrumental effect remains unclear.

In Fig. 3 we compare the atmospheric parameters of US 708 to those of other HesdO, sdO and sdB stars analysed from high resolution spectra by Lisker et al. (2005) and Ströer et al. (2005). As can be seen the effective temperature of US 708 is very similar to that of most HesdO stars, whereas its gravity is slightly lower. Nevertheless, we regard the atmospheric parameters of US 708 as typical for sdO stars.

In order to calculate the distance of US 708 we need to know its apparent visual magnitude as well as its mass. From the star's *ugriz* magnitudes we calculate its apparent visual magnitude $V = 19^{\mathrm{m}}0$ using the calibration of Smith et al. (2002). For the mass we assume the canonical mass of 0.5 $M_{\odot}$ suggested by evolutionary models (Dorman et al. 1993). Using the mass, the effective temperature, gravity and apparent
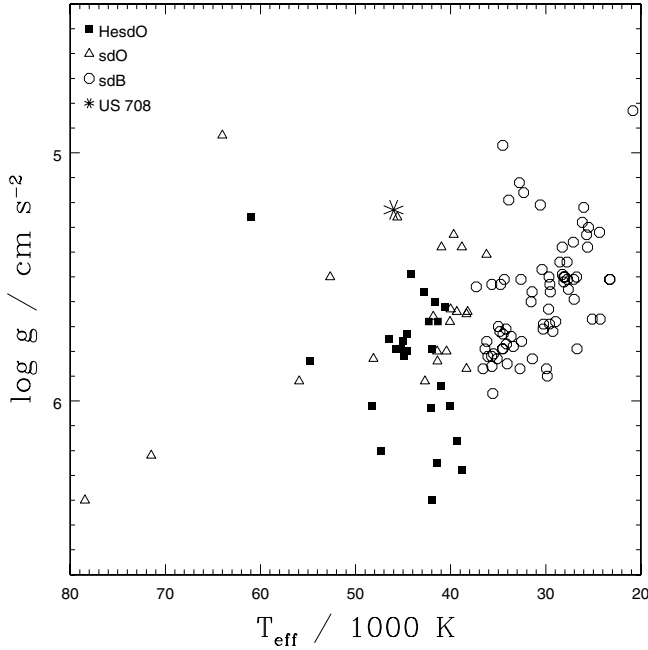
Fig. 3. T_{eff}–$\log g$-diagram of subluminous stars analyzed by Lisker et al. (2005) and Ströer et al. (2005). sdB stars are denoted by open circles, sdO stars by open triangles and HesdO by filled squares. US 708 is marked by a star.

magnitude, we derive the distance to be $19.3^{+3.1}_{-2.7}$ kpc. The star's distance from the Galactic centre is 25.8 kpc and it is located 14.1 kpc above the Galactic plane.

Correcting for the solar reflex motion and to the local standard of rest (Dehnen & Binney 1998), the Galactic velocity components can be derived from the radial velocity ($U = -471$ km s^{-1}, $V = 259$ km s^{-1} and $W = 525$ km s^{-1}, U positive towards the GC and V in the direction of Galactic rotation) resulting in a Galactic rest-frame velocity of 751 km s^{-1}, indicating that US 708 is unbound to the Galaxy because the escape velocity at a galactocentric distance of 25 kpc is $\approx$430 km s^{-1} Allen & Santillan (1991).

4. Space motion

Proper motion measurements are needed to reconstruct the full space velocity vector and trace the trajectory of US 708 back to its birth place. The USNO-B1.0 catalog (Monet et al. 2003) lists $\mu_\alpha \cos(\delta) = -6 \pm 1$ mas yr^{-1} and $\mu_\delta = 2 \pm 3$ mas yr^{-1}. Given the faintness of the star, we regard the catalog errors as too optimistic and plausible errors to be larger than the measured components. Since the SMBH in the Galactic centre is the most likely accelerator for a HVS, we reconstructed the path of US 708 from the GC by varying the proper motion components.

Calculations were performed with the program ORBIT6 developed by Odenkirchen & Brosche (1992). This numerical code calculates the orbit of a test body in the Galactic potential from Allen & Santillan (1991). The complete set of cylindrical coordinates is integrated and positions and velocities are

computed in equidistant time steps. Trial values for the unknown proper motions were varied until the star passed through the GC with an accuracy of better than 10 pc, see Edelmann et al. (2005) for details. The resulting time of flight is 32 Myrs with a predicted proper motion of $\mu_\alpha \cos(\delta) = -2.2$ mas yr^{-1} and $\mu_\delta = -2.6$ mas yr^{-1}. Because US 708 is the closest known HVS, its proper motion may provide the first constraint on the shape of the Galactic potential using HVS as proposed by Gnedin et al. (2005).

5. Evolution of subluminous O stars

Before discussing the origin of US 708 further, we shall discuss the evolutionary status of sdO stars. They are generally believed to be closely linked to the sdB stars. The latter have been identified as Extreme Horizontal Branch (EHB) stars (Heber 1986), i.e. they are core helium burning stars with hydrogen envelopes too thin to sustain hydrogen burning (unlike normal EHB stars). Therefore they evolve directly to the white dwarf cooling sequence avoiding the Asymptotic Giant Branch (AGB). It may, however, be premature to assume that all the hotter sdO stars are descendants of the sdB stars in the process of evolving into white dwarfs. While the sdB stars spectroscopically form a homogenous class, a large variety of spectra is observed among sdO stars (Heber et al. 2005). Most subluminous B stars are helium deficient, whereas only a small fraction of sdO stars are. Most of the latter are helium rich including a large fraction of helium stars (HesdO), i.e. stars for which no hydrogen Balmer line blends to the He II Pickering series are detectable. Heber et al. (2005) summarized the results of recent spectroscopic analyses and provided evidence that the HesdOs are a population different from the sdO and sdB stars, both because of their distribution in the (T_{eff}, $\log g$) diagram and their binary frequency. While the HesdO stars cluster near $T_{eff} = 45\,000$ K, the sdO stars are widely spread (see Fig. 3). The fraction of sdB stars in short period binaries ($P < 10d$) is high. (Maxted et al. 2001) found 2/3 of their sdB sample in be such binaries, whereas Napiwotzki et al. (2004) found a somewhat lower fraction of 40%. Amongst the sdO stars a similarly large fraction was found, whereas only one HesdO star was found to be in a close binary implying a fraction of less than 5%. Obviously, binary evolution plays an important role for the formation of sdB stars and possibly also for that of the sdO stars. A recent population synthesis study (Han et al. 2003) identified three channels to form sdB stars: (i) one or two phases of common envelope evolution; (ii) stable Roche lobe overflow; and (iii) the merger of two helium-core white dwarfs. The latter could explain the population of single stars. The simulations by (Han et al. 2003) cover the observed parameter range of sdB stars but fail to reproduce their distribution in detail. Due to the lack of binaries it may be tempting to consider the HesdO stars as having formed by such mergers although their distribution does not agree very well with the predictions from simulations (Ströer et al. 2005). Neutron stars are known to travel at extreme velocities because they are ejected by asymmetric supernova kicks. SdO stars are remnants of low mass stars and do not suffer from supernova explosions.

6. The origin of US 708

In Sect. 4 we have shown that US 708 could have originated from the Galactic center and reached its present position in about 30 Myrs. Hills (1988) predicted that hyper-velocity stars should exist if the Galactic centre hosts a super-massive black hole (SMBH), because tidal disruption of a binary interacting with the SMBH in the centre of our Galaxy can lead to ejection velocities as high as $4000 \, \mathrm{km \, s^{-1}}$. Yu & Tremaine (2003) confirmed this and predicted production rates of up to 10^{-5} HVS/yr. They also explored the encounter of a single star with a binary SMBH and derived even higher HVS production rates. Recently, Gualandris et al. (2005) performed three-body scattering experiments for the tidal disruption of a binary system by the SMBH and an encounter of a single star with a binary black hole and find that the the former ejects HVSs at higher velocities than the latter, but had a somewhat smaller ejection rate. Gualandris et al. (2005) also explore the properties of stellar mergers in encounters between stellar binaries and the SMBH. In their experiment, tailored to the properties of the HVS SDSS J090745.0+024507, they considered equal mass binaries of $1.5 \, M_\odot$. Merger occur only in the closest systems (initial separations $0.03 \, \mathrm{AU} < a < 0.05 \, \mathrm{AU}$) and only 6% (in this range of separation) of the encounters result in a binary merger with escape of the collision product. Hence they find this process to be very inefficient.

The kinematical experiments presented in Sect. 4 have shown that US 708 may indeed originate from the Galactic centre and travel for about 30 Myrs to reach its present position in the halo. Hence, the ejection scenarios (described above) are viable for US 708. Since the merger scenario appears attractive to explain the evolutionary origin of the HesdO stars, the possibility exists that the merger of a close binary consisting of two helium white dwarfs occurred during the encounter with the central SMBH. The sdO evolutionary life time of about 100 Myrs is consistent with its time-of-flight.

7. Conclusion

In the context of a spectroscopic study of sdO stars from the *SDSS* we discovered a new hyper-velocity star, US 708, with a heliocentric radial velocity of $+708 \pm 15 \, \mathrm{km \, s^{-1}}$ at a distance of about 20 kpc. Keck *LRIS* spectra showed it to be extremely helium-rich (He/H = 10 by number). The star is unbound to the Galaxy as its Galactic rest frame velocity (at least $757 \, \mathrm{km \, s^{-1}}$) exceeds, the local Galactic escape velocity (about $430 \, \mathrm{km \, s^{-1}}$). A kinematical experiment showed that US 708 could have been ejected from the Galactic center, probably by tidal interaction with the central super-massive black hole, if its proper motion were $\mu_\alpha \cos(\delta) = -2.2 \, \mathrm{mas \, yr^{-1}}$ and $\mu_\delta = -2.6 \, \mathrm{mas \, yr^{-1}}$. This scenario requires that the star originally was in a binary that was disrupted by tidal interaction with the SMBH and the sdO component was ejected. However, the binary fraction of sdO stars is very low. In fact, the merger of two helium-core white dwarfs is a popular scenario for the formation of sdO stars. If the sdO was formed by such a merger before interaction with the SMBH, it would require the SMBH to be a binary. Yu & Tremaine (2003) showed that this scenario would be quite efficient in producing hyper-velocity stars. However, the binary nature of the SMBH in the GC is purely speculative. Alternatively, we considered the possibility that US 708, indeed may be a merger product, but the merger was induced by the interaction with the super-massive black hole in the GC and then the star escaped. Theoretical simulations are urgently needed to check whether tidal interaction between a short period binary consisting of two helium-core white dwarfs with the SMBH would efficiently produce mergers.

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