

LETTER TO THE EDITOR

**LMC origin of the hyper-velocity star HE 0437–5439<sup>★</sup>**  
**Beyond the supermassive black hole paradigm**

N. Przybilla<sup>1</sup>, M. F. Nieva<sup>1</sup>, U. Heber<sup>1</sup>, M. Firnstein<sup>1</sup>, K. Butler<sup>2</sup>, R. Napiwotzki<sup>3</sup>, and H. Edelmann<sup>1</sup>

<sup>1</sup> Dr. Remeis-Sternwarte Bamberg, Sternwartstr. 7, D-96049 Bamberg, Germany

<sup>2</sup> Universitätssternwarte München, Scheinerstr. 1, D-81679 München, Germany

<sup>3</sup> Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK

Received... ; accepted ...

**ABSTRACT**

**Context.** Hyper-velocity stars move so fast that only a supermassive black hole (SMBH) seems to be capable to accelerate them. Hence the Galactic centre (GC) is their only suggested place of origin. Edelmann et al. (2005) found the early B-type star HE 0437–5439 to be too short-lived to have reached its current position in the Galactic halo if ejected from the GC, except if being a blue straggler star. Its proximity to the Large Magellanic Cloud (LMC) suggested an origin from this galaxy.

**Aims.** The chemical signatures of stars at the GC are significantly different from those in the LMC. Hence, an accurate measurement 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 are analysed using state-of-the-art non-LTE modelling techniques.

**Results.** We measured 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, respectively. 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 life time 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 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) to accelerate stars to hyper-velocity speed than the SMBH. We draw attention to dynamical ejection from dense massive clusters, that has recently been proposed by Gvaramadze et al. (2008).

**Key words.** Galaxy: halo – Magellanic Clouds – stars: abundances, distances, early-type, individual (HE 0437–5439)

**1. Introduction**

Stars moving faster than the Galactic escape velocity were first predicted to exist by Hills (1988). The first such hyper-velocity stars (HVSs) were discovered serendipitously only recently (Brown et al. 2005; Hirsch et al. 2005; Edelmann et al. 2005, E05: HE 0437–5439 at  $723 \text{ km s}^{-1}$  heliocentric radial velocity). A systematic search for such objects has resulted in the discovery of seven additional HVS up to 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 a SMBH.

Both, the moderate rotational velocity ( $v \sin i = 54 \text{ km s}^{-1}$ ) and the chemical composition (consistent with solar abundances within a factor of a few from a LTE analysis of a spectrum with  $S/N \approx 5$ ) were considered evidence for a main sequence nature of HE 0437–5439 (E05). This put the star at a distance of  $\approx 60 \text{ kpc}$ .

Numerical kinematical experiments were carried out to trace the trajectory of HE 0437–5439 from the GC to its present lo-

cation in the Galactic halo. However, its travel time (100 Myrs) was found to be much longer than its main sequence lifetime ( $\approx 25\text{--}35 \text{ Myrs}$ ), rendering a GC origin unlikely, though possible if HE 0437–5439 would be a blue straggler star. Alternatively the star could have originated from the Large Magellanic Cloud (LMC) as it is much closer to this galaxy (18 kpc) than to the GC.

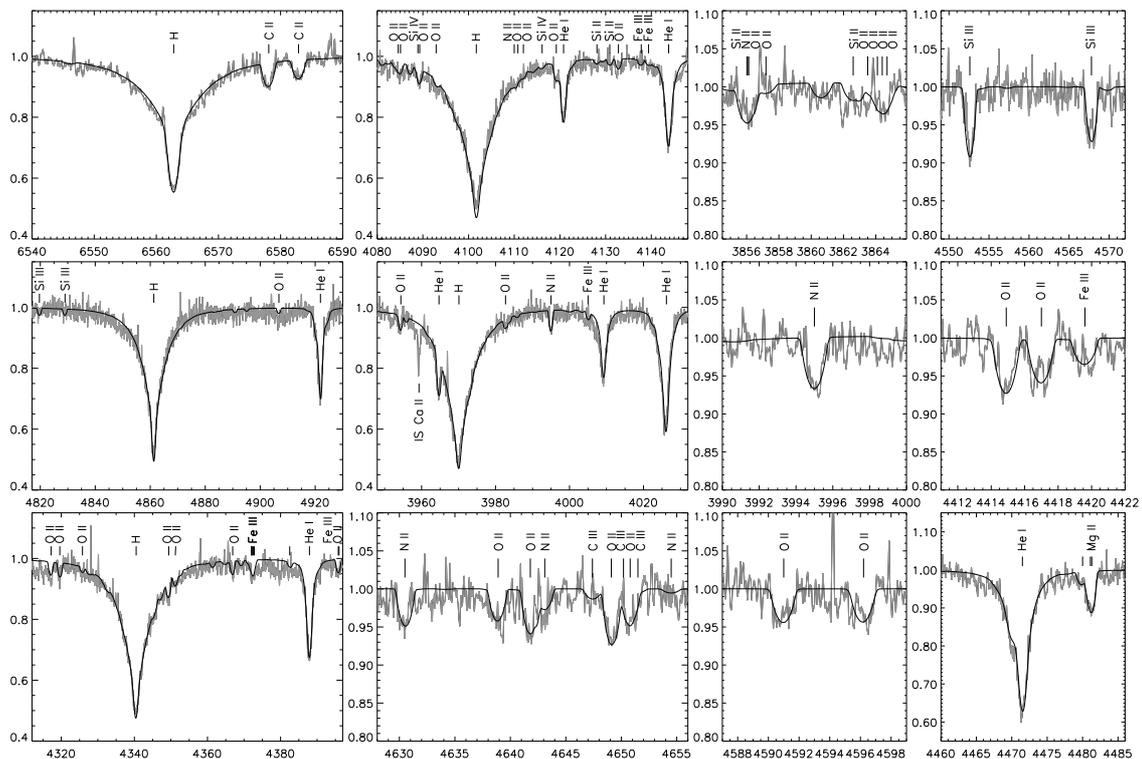
An accurate determination of its elemental abundance pattern should allow to distinguish between an origin in the LMC or in the GC because their chemical compositions differ distinctively. HE 0437–5439 is by far the brightest HVS known ( $V = 16.36$ , Bonanos & López-Morales 2008) and therefore suited best for a detailed analysis. Hence 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  $\sim 4 \text{ h}$  were obtained on January 12, 2006, covering the range from 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 normali-

Send offprint requests to: przybilla@sternwarte.uni-erlangen.de

<sup>★</sup> Based on observations collected at the European Southern Observatory, Paranal, Chile (DDT proposal 276.B-5024).



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

sation in the blue could be achieved, a region containing many broad Balmer lines. Moreover, the method removes fringes in the red reliably, improving considerably on the standard UVES data reduction pipeline. A peak S/N of  $\approx 80$  per resolution element is measured for the coadded spectrum in the blue.

Two comparison stars with similar atmospheric parameters are 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 used for HE 0437–5439 are applied to the UVES spectrum of NGC 2004-D15, obtained from the ESO archive. A comparison with the LMC star allows 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 ionization 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 and therefore atmospheric parameters and elemental abundances to be determined with small uncertainties.

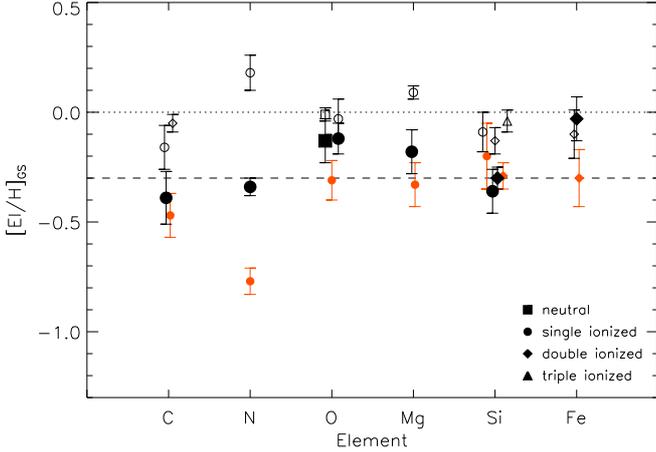
The atmospheric parameters ( $T_{\text{eff}}$ ,  $\log g$ ) were determined from metal ionization equilibria (mainly Si II/III/IV, but also O I/II

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

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

and C II/III, where available) and the Stark-broadened Balmer lines. Microturbulence  $\xi$  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  $\chi^2$ -minimisation of fits to individual metal line profiles.

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  $61 \pm 9$  kpc, in perfect agreement with E05.



**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.

The uncertainties in the atmospheric parameters were constrained by the quality of the simultaneous fits to all diagnostic indicators: all hydrogen and helium lines, and multiple metal ionization equilibria. Such a good match has been reported never before in B-star analyses. The helium abundance in the three stars was found to be consistent with the solar value. Standard deviations  $\sigma$  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 to minimise 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 with respect to previous B star analyses can be obtained only 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)<sup>1</sup>. Note the small line-to-line-scatter and the agreement of abundances for different ions of the elements, *simultaneously* for all ionization equilibria. This can be achieved only when the stellar parameters are constrained well and highly reliable model atoms are employed in the non-LTE calculations. Metal ionization 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  $T_{\text{eff}}$  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 is in general agreement with the baseline metallicity derived in previous studies of early-type

<sup>1</sup> Similar conclusions are drawn in the following if the revised solar abundances of Grevesse et al. (2007) are used.

stars in the LMC. Nitrogen is known to have a low pristine abundance in the LMC (e.g. K02). We thus confirm NGC 2004-D15 to be 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 shall 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.

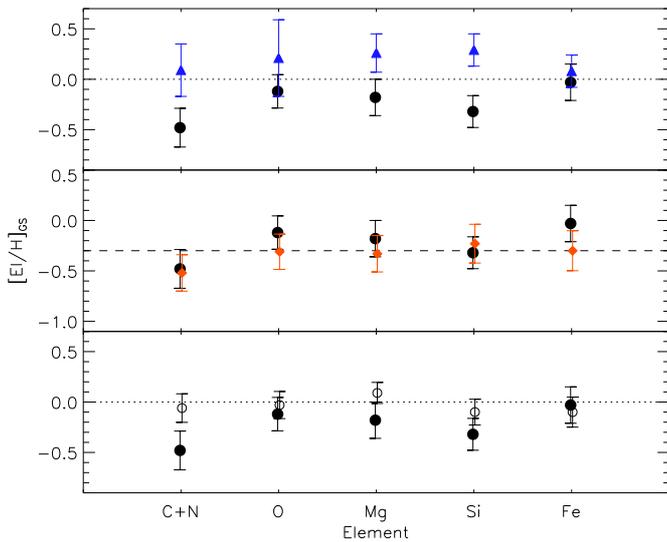
**The Galactic centre.** A comparison of the abundance pattern of HE 0437–5439 to that of a sample of stars near the GC (Cunha et al. 2007; Najarro et al. 2008) is depicted in Fig. 3 (upper panel), for average values over all ions of an element. The sum of carbon and nitrogen is considered to remove signatures of mixing with nuclear-processed matter from the individual abundances (as catalysts, their total number is conserved in the CN-cycle). The  $\alpha$ -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 with respect to iron. This rules out HE 0437–5439 to be 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 as 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 an origin of HE 0437–5439 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 to 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 the LMC as place of origin solely because of the discrepancy between evolutionary life time 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 has also to account for the large space motion of the LMC (e.g. Piatek et al. 2008) of about 500 pc/Myr in direction east-north-east. The total distance to travel by HE 0437–543 after ejection  $\sim 18$  Myr ago is therefore  $\sim 19_{-3}^{+7}$  kpc. Hence, the total ejection velocity should amount to  $\sim 1000 \text{ km s}^{-1}$ , if originating in the kinematic centre of the LMC. Accounting for the extension of the LMC, ejection velocities may vary by  $\sim 100 \text{ km s}^{-1}$ .



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

Flight times from the outer Galactic disk to the current position of HE 0437–5439 are depicted in Fig. 4 of E05, who 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 life times are about the same as the time of flight, rendering an origin in the Galaxy very unlikely.

## 5. Conclusion

We have performed a quantitative spectral analysis of the HVS HE 0437–3954 and reference objects in the LMC and the solar neighbourhood. Use of 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  $\alpha$ -enrichment. On the other hand a high degree of consistency with the LMC pattern is found when accounting for an abundance scatter within the LMC<sup>2</sup>. The observed abundance pattern could also be consistent with an origin from the outskirts of the Galactic disk, in the case HE 0437–3954 being a blue straggler. However, a comparison of the time-of-flight with the life time of the blue straggler practically rules out this scenario. Hence, HE 0437–3954 is unlikely of 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  $1000 \text{ km s}^{-1}$  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.

<sup>2</sup> 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.

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 a SMBH are ruled out. Hence there must be an additional physical mechanism capable of accelerating a massive star to a space velocity of  $1000 \text{ km s}^{-1}$ .

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 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 be of the right age to qualify as candidate place of birth of 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 such simple probes for the shape of the Galactic halo as suggested e.g. by Gnedin et al. (2005). The fundamental assumption of the exclusive origin of HVSs in the GC has to be dropped, as acceleration may occur in clusters throughout the Galactic disk as well.

*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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