

# Discovery of two embedded clusters with *WISE* in the high Galactic latitude cloud HRK 81.4–77.8

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## ABSTRACT

Molecular clouds at very high latitude ( $b > 60^\circ$ ) away from the Galactic plane are rare and in general are expected to be non-star-forming. However, we report the discovery of two embedded clusters (Camargo 438 and Camargo 439) within the high-latitude molecular cloud HRK 81.4–77.8 using *WISE*. Camargo 439 with Galactic coordinates  $\ell = 81^\circ.11$  and  $b = -77^\circ.84$  is an  $\sim 2$  Myr embedded cluster (EC) located at a distance from the Sun of  $d_\odot = 5.09 \pm 0.47$  kpc. Adopting the distance of the Sun to the Galactic Centre  $R_\odot = 7.2$  kpc, we derive for Camargo 439 a Galactocentric distance of  $R_{GC} = 8.70 \pm 0.26$  kpc and a vertical distance from the plane of  $-4.97 \pm 0.46$  kpc. Camargo 438 at  $\ell = 79^\circ.66$  and  $b = -78^\circ.86$  presents similar values. The derived parameters for these two ECs put HRK 81.4–77.8 in the halo at a distance from the Galactic Centre of  $\sim 8.7$  kpc and  $\sim 5.0$  kpc from the disc. Star clusters provide the only direct means to determine the high-latitude molecular cloud distances. The present study shows that the molecular cloud HRK 81.4–77.8 is currently forming stars, apparently an unprecedented event detected so far among high-latitude clouds. We carried out a preliminary orbit analysis. It shows that these ECs are the most distant known ECs from the plane and both cloud and clusters are probably falling ballistically from the halo on to the Galactic disc, or performing a flyby.

**Key words:** ISM: clouds – ISM: kinematics and dynamics – open clusters and associations: general.

## 1 INTRODUCTION

Intermediate- and high-latitude molecular clouds (HLCs) are small and low gas density structures that may be in the transition between molecular to atomic clouds (Sakamoto 2002). Most of them appear to be non-star-forming clouds (Magnani et al. 2000). Their origins are still not well understood, but a possible explanation is that violent events as supernovae explosions within the Galactic disc may throw dust away, which during the free-fall phase can merge to form molecular/dust clouds. This model is known as Galactic fountain (Shapiro & Field 1976; Bregman 1980). Melioli et al. (2008) suggest that a typical fountain powered by 100 Type II supernovae from a single OB association may eject material up to  $\sim 2$  kpc (Quilis & Moore 2001; Pidopryhora, Lockman & Shields 2007). However, an extragalactic origin is also possible (Oort 1970; Kaufmann et al. 2006) with the infall gas condensing to form clouds, which fall to the Galactic disc (see also Lockman et al. 2008; Nichols et al. 2014).

Star formation in very high Galactic latitude molecular clouds provides the only direct means to determine their distances, but as far as we are aware no such an event has been detected.

Blitz, Magnani & Mundy (1984) identified 457 HLC (including intermediate latitudes) candidates and Magnani, Hartmann & Speck (1996) constructed a catalogue of about 100 clouds. In the absence of star formation, distances to the Galactic plane and Sun can only be estimated by means of statistical modelling. One observational approach is spectral absorptions by a foreground hot star (e.g. Danly 1992). An alternative is photometric detection of reddening of stars along the line of sight (e.g. Schlafly et al. 2014). However, the lack of direct cloud distances remains a challenge. The only detected star-forming cases at intermediate Galactic latitudes are MBM 12 (Luhman 2001), which is a small association at  $b = -33^\circ.8$ , and MBM 20 (McGehee 2008; Malinen et al. 2014) at  $b = -36^\circ.5$ .

High-velocity clouds (HVCs) were discovered in 1963 (Muller, Oort & Raimond 1963). Models of HVCs also naturally predict lower radial velocity halo clouds (LVHC). Similarly to HVCs, expectations are that *IRAS* fluxes tend to be lower as compared to H I column densities in LVHCs. Peek et al. (2009) found LVHCs based on such low dust to gas ratios.

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In this paper, we communicate the discovery of two embedded clusters in the direction of the low-velocity high-latitude molecular/H I cloud HRK 81.4–77.8 (Heiles, Reach & Koo 1988), also known as G 81.4 – 77.8 or Gal 081.40 – 77.80 – see e.g. Simbad.<sup>1</sup> Heiles, Reach & Koo (1988) provided a radial velocity of  $v_{\text{LSR}} = -8 \text{ km s}^{-1}$ . The equatorial position is  $\alpha(2000) = 0^{\text{h}}17^{\text{m}}32^{\text{s}}$  and  $\delta(2000) = -17^{\circ}43'18''$ . HRK 81.4–77.8 is an isolated molecular cloud located in Cetus (Heiles, Reach & Koo 1988). No distances are available for HRK 81.4–77.8. We detected the embedded clusters (ECs) with *WISE*, and by means of stellar photometry with the 2MASS and *WISE* catalogues, we computed their colour–magnitude diagrams (CMDs) and radial density profile (RDP).

The two new clusters are Camargo 438 and Camargo 439, hereafter C 438 and C 439, respectively. The cluster designation and numbering follow the recent catalogue of young clusters that we found in *WISE* (Camargo, Bica & Bonatto 2015).

The systematic detection of the pré-main sequence (PMS) stellar content in ECs have become a major achievement by our group (e.g. Bica, Bonatto & Camargo 2008; Bica & Bonatto 2011; Bonatto & Bica 2010, 2011b; Camargo, Bonatto & Bica 2009, 2010, 2011, 2012; Camargo, Bica & Bonatto 2013; Camargo et al. 2015). What characterizes our analysis is decontamination of field stars. Recently, we dedicated attention to ECs essentially seen in *WISE* images (Camargo et al. 2015). We discovered 437 such clusters in the Galactic disc. We now turn our attention to high-latitude clouds ( $b > 60^{\circ}$ ), knowing the capacity of our approach, and the lack as yet of direct distances and star formation for halo clouds.

In Section 2, we communicate the two new clusters and carry out CMD and RDP analyses. In Section 3, compute and discuss possible cloud orbits and in Section 4, we provide concluding remarks.

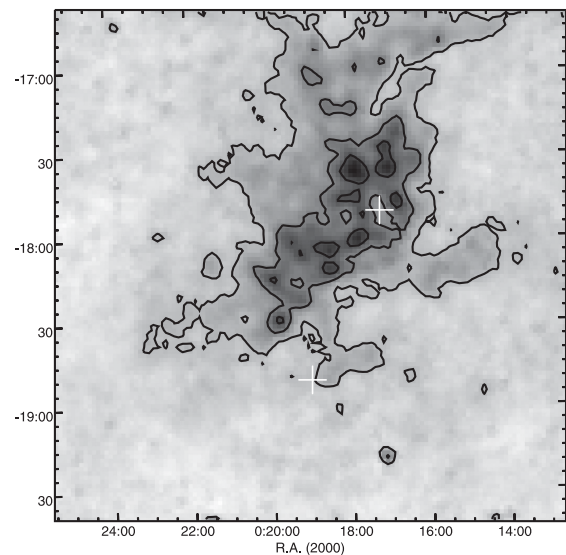
## 2 DISCOVERY OF TWO YOUNG STAR CLUSTERS

In this work, we communicate the discovery of two ECs in the high-latitude molecular cloud HRK 81.4–77.8. The existence of ECs at large distances from the Galactic plane is of considerable importance because it may provide information about the physical conditions and processes that are taking place in HLCs and how such a halo component behaves in the Galaxy. These ECs may provide a direct measurement of the scaleheight and distance to HLCs. Following our recent catalogue (Camargo et al. 2015) we adopt the designations C 438 and C 439 for the newly discovered ECs.

In the Galaxy most young open clusters and ECs are located within the range of 200 pc from the Galactic plane (e.g. Camargo et al. 2013).

Fig. 1 shows in detail the *IRAS* 100  $\mu\text{m}$  image of the molecular/H I cloud HRK 81.4–77.8. The cluster C 439 is located within the central region of a ring-like structure of dense gas clumps. Cloud structures like that are common around ECs and are in general related to feedback of massive stars. C 438 is located at the southern border of the molecular cloud. Given the relative isolation of HRK 81.4–77.8, halo stars are probably not the driving mechanism responsible for its star formation. Besides, the present star formation is most likely the first, since the most massive stars have not yet reached the main sequence (see Fig. 3).

The *WISE* bands W1 (3.4  $\mu\text{m}$ ) and W2 (4.6  $\mu\text{m}$ ) are more sensitive to the stellar component while W3 (12  $\mu\text{m}$ ) and W4 (22  $\mu\text{m}$ ) show



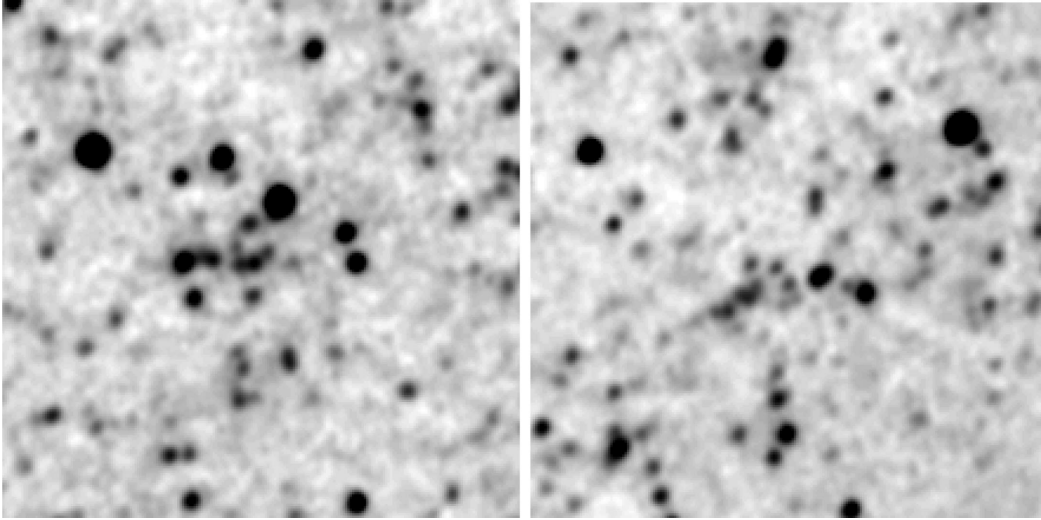
**Figure 1.** *IRAS* 100  $\mu\text{m}$  ( $2^{\circ}5 \times 2^{\circ}5$ ) image showing in detail the structure of HRK 81.4 – 77.8. The plus signs indicate the position of C 439 (top) and C 438 (bottom).

rather dust emission. In Fig. 2, we show *WISE* W1 images of the newly found ECs. We show in Table 1, the equatorial positions of C 438 and C 439. The Galactic coordinates of C 439 are  $\ell = 81^{\circ}.11$  and  $b = -77^{\circ}.84$  and for C 438 are  $\ell = 79^{\circ}.66$  and  $b = -78^{\circ}.86$ . The cloud is present in the *WISE* W3 and W4 bands. Star formation in the cloud is expected to be related to cold and warm dust emission, since massive clusters may produce more massive (hot) stars that, in turn, heat the surrounding dust to higher temperatures than those expected in less massive clusters.

In Figs 3 and 4 are shown CMDs and RDPs for both ECs following our previous studies. The CMDs are built with 2MASS photometry. The upper-left panels give CMDs extracted from a circular area centred on the coordinates of each EC. The upper-right panel of each figure presents the RDP for the respective cluster. The bottom panels give the decontaminated CMDs built applying the field star decontamination algorithm to the raw photometry. It is described in detail in Bonatto & Bica (2007, 2008, 2010) and Bica et al. (2008) and has been used in several works (e.g. Camargo et al. 2009, 2010, 2011, 2012, 2013; Bica & Bonatto 2011; Bonatto & Bica 2009, 2011a, and references therein). The fundamental parameters (age, reddening, distance) are derived by fitting PARSEC isochrones (Bressan et al. 2012) to the cluster sequences in the decontaminated CMD. The fits are made by eye allowing for differential reddening and photometric uncertainties (Camargo et al. 2010, 2011). We apply magnitude and colour shifts to the MS+PMS isochrone set from zero distance modulus and reddening until a satisfactory solution is reached. The parameter errors have been estimated by displacing the best-fitting isochrone in colour and magnitude to the limiting point where the fit remains acceptable. The best solution for each cluster is shown in Table 1.

The decontaminated CMDs of C 439 (Fig. 3) fitted by PARSEC isochrones provide an age of  $2 \pm 1$  Myr for a distance from the Sun of  $5.1 \pm 0.5$  kpc. Adopting  $R_{\odot} = 7.2$  kpc (Bica et al. 2006) we derive a Galactocentric distance of  $R_{\text{GC}} = 8.70 \pm 0.26$  kpc with spatial components  $x_{\text{GC}} = -7.05 \pm 0.02$  kpc,  $y_{\text{GC}} = 1.06 \pm 0.10$  kpc, and  $z_{\text{GC}} = -4.97 \pm 0.46$  kpc. Nevertheless, if we adopt  $R_{\odot} = 8.0$  kpc we derive  $R_{\text{GC}} = 9.34 \pm 0.25$  kpc with spatial components  $x_{\text{GC}} = -7.83 \pm 0.02$  kpc,  $y_{\text{GC}} = 1.06 \pm 0.10$  kpc, and

<sup>1</sup> <http://simbad.u-strasbg.fr/simbad/sim-fcoo>



**Figure 2.** The new embedded clusters. Left: *WISE* W1 (5 arcmin  $\times$  5 arcmin) image centred on the C 439 coordinates. Right: the same for C 438.

**Table 1.** Position and derived fundamental parameters for the two ECs.

Cluster	$\alpha(2000)$	$\delta(2000)$	$A_V$	Age	$d_{\odot}$	$R_{GC}$	$x_{GC}$	$y_{GC}$	$z_{GC}$	$N$	$M$
(1)	(h m s)	( $^{\circ}$ $'$ $''$ )	(mag)	(Myr)	(kpc)	(kpc)	(kpc)	(kpc)	(kpc)	(stars)	( $M_{\odot}$ )
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
C 438	00:19:17	-18:47:55	$0.99 \pm 0.03$	$2 \pm 1$	$5.09 \pm 0.70$	$8.69 \pm 0.40$	$-07.04 \pm 0.02$	$+0.97 \pm 0.13$	$-4.99 \pm 0.69$	33	56
C 439	00:17:30	-17:49:18	$0.99 \pm 0.03$	$2 \pm 1$	$5.09 \pm 0.47$	$8.70 \pm 0.26$	$-07.05 \pm 0.02$	$+1.06 \pm 0.10$	$-4.97 \pm 0.46$	42	260

Notes. Cols. 2 and 3: Central coordinates; Col. 4:  $A_V$  in the cluster's central region. Col. 5: age, from 2MASS photometry. Col. 6: distance from the Sun. Col. 7:  $R_{GC}$  calculated using  $R_{\odot} = 7.2$  kpc as the distance of the Sun to the Galactic Centre. Cols. 8–10: Galactocentric components. Cols. 11 and 12: number of candidate cluster members and cluster mass.

$z_{GC} = -4.97 \pm 0.46$  kpc. Usually we analyse the cluster structure by fitting a King-like profile to the cluster RDP (King 1962). However, the RDP of C 439 is irregular and does not follow a King's profile, which is expected for such young cluster. Nevertheless, it was possible to estimate the probable cluster radius as  $R_{RDP} \sim 10$  arcmin.

The analysis of the decontaminated CMDs of C 438 (Fig. 4) provide an age of  $2 \pm 1$  Myr and a distance of  $d_{\odot} = 5.1 \pm 0.7$  kpc. We derive  $R_{GC} = 8.69 \pm 0.4$  kpc and spatial components  $x_{GC} = -7.04 \pm 0.02$  kpc,  $y_{GC} = 0.97 \pm 0.13$  kpc, and  $z_{GC} = -4.99 \pm 0.69$  kpc considering  $R_{\odot} = 7.2$  kpc. Adopting  $R_{\odot} = 8.0$  kpc we derive a Galactocentric distance of  $R_{GC} = 9.33 \pm 0.37$  kpc with spatial components  $x_{GC} = -7.82 \pm 0.02$  kpc,  $y_{GC} = 0.97 \pm 0.13$  kpc, and  $z_{GC} = -4.99 \pm 0.69$  kpc. The RDP of C 438 is as well irregular, but shows a central peak. We estimate a cluster radius of  $R_{RDP} \sim 12$  arcmin. Fig. 5 shows dust emission in the central region of C 438 with the *WISE* W3 band, which confirms its embedded nature.

We estimate the cluster mass by counting stars in the decontaminated CMD (within the region  $R < R_{RDP}$ ) of each EC. For the MS, the stellar masses are estimated from the mass–luminosity relation implied by the respective isochrone solutions, while for the PMS stars, we adopted an average mass value, as follows. Assuming that the mass distribution of the PMS stars follows Kroupa, Aarseth & Hurley (2001) MF, the average PMS mass – for masses within the range  $0.08 \lesssim m(M_{\odot}) \lesssim 7$  is  $\langle m_{PMS} \rangle \approx 0.6 M_{\odot}$  (see Bonatto & Bica 2010; Camargo et al. 2011). The estimated mass and probable clusters members are shown in Table 1.

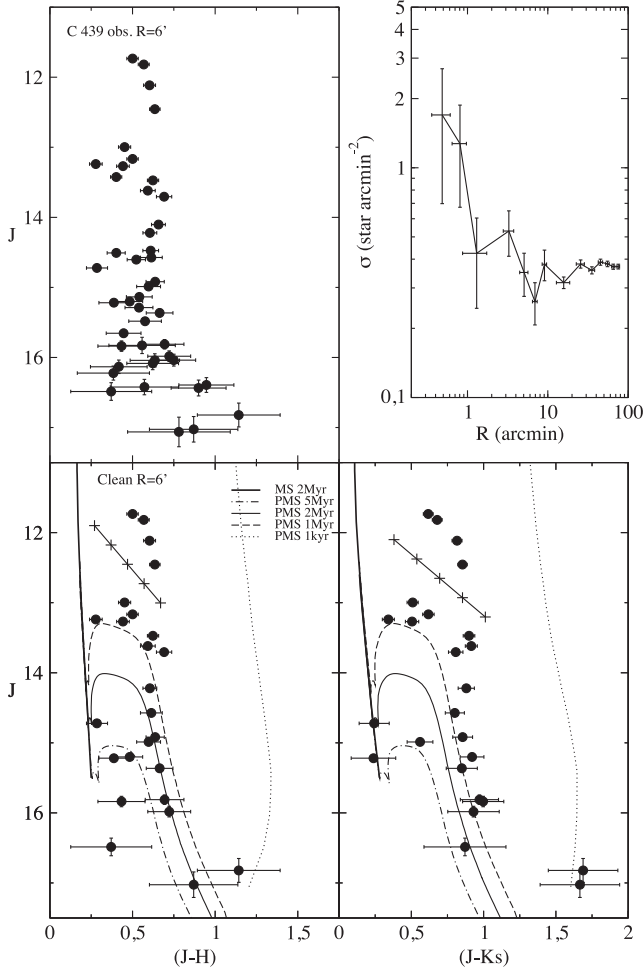
HRK 81.4–77.8 is located in the annular region where, according to Kalberla et al. (2007) the Galactic disc gas accretion rate presents a peak ( $6 < R < 11$  kpc). The velocity of this high-latitude cloud agrees with that derived by Kaufmann et al. (2006) for the infall rotating gas cloud, for which the orbital velocity decreases as a function of height from the disc.

### 3 A PRELIMINARY ORBIT

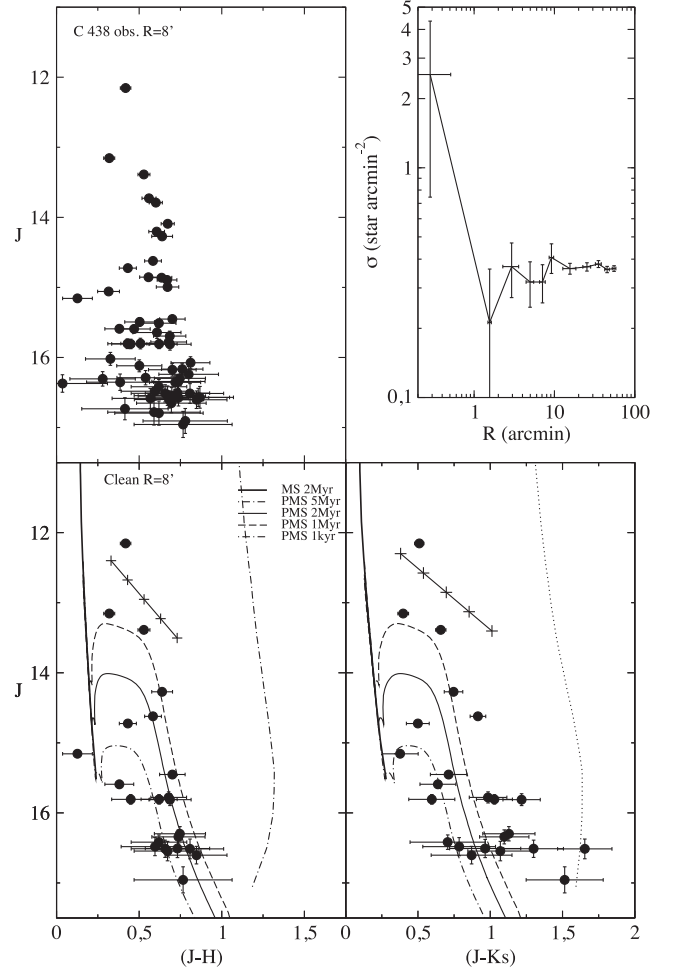
The past motion of HRK 81.4–77.8 probably played an important role in the transition from atomic to molecular cloud (Röhser et al. 2014, and references therein). Heitsch & Putman (2009) argue that most H I HVCs are disrupted after falling for 100 Myr and moving for  $\sim 10$  kpc. Since star-forming clouds may be successively decelerated due to fragmentation as an infalling cloud is being disrupted, slower clouds tend to be longer-lived because of their low mass-loss rates. On the other hand, the disruption time-scale decreases with increasing halo density, as a consequence of dragging forces. After loss of the H I content the remnants may form a warm ionized LVC in the hot coronal gas and eventually may fall in the ionized Galactic disc.

In this section, we compute the possible orbital motion of the molecular cloud and its two ECs. For details on the Galactic potential and other procedures see Salerno et al. (2009).

We show in Fig. 6, the cloud orbit in the Galactic potential using  $V_{LSR} = -8$  km s $^{-1}$  and null transversal velocities. This favours a Galactic Chimney model (Normandeau, Taylor & Dewdney 1996) for the origin of the cloud, since in this interpretation the coincidence of the cloud and the disc should have occurred  $\sim 48$  Myr ago. Note



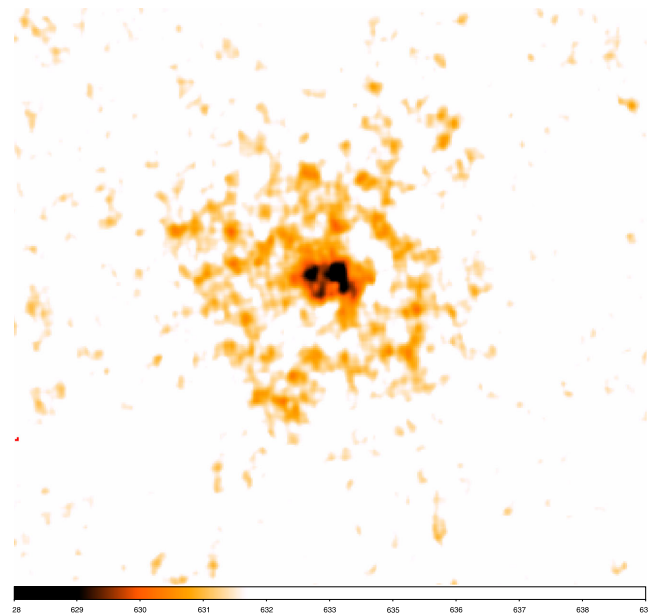
**Figure 3.** 2MASS CMDs and RDP for the newly found EC C 439. Top panels: observed CMD  $J \times (J - H)$  (left) and RDP (right). Bottom panels: field-star decontaminated CMDs fitted with Padova isochrones. We also show the reddening vector for  $A_v = 0-5$ .



**Figure 4.** Same as Fig. 3 for C 438.

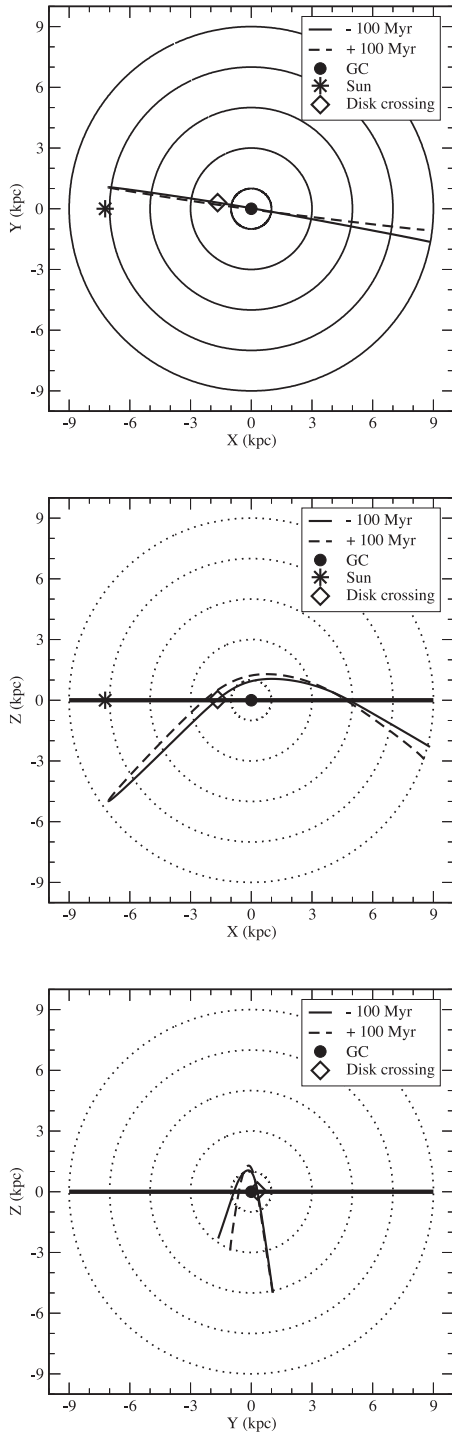
that this locus lies in the inner Galactic disc, where a cloud would not be expected to survive disc shocking.

In Fig. 7, we show the cloud motion for  $V_{LSR} = -8 \text{ km s}^{-1}$  together with the proper motions of UCAC4 for two stars that have counterparts in our decontaminated CMD (Fig. 3). The available proper motions and other data for the stars in the area of C 439 are given in Table 2. Fig. 7 uses the proper motion of the first and third stars in Table 2. Uncertainties are significant; however, we tentatively compute the orbit using also this non-null components for the transverse velocity. The orbital solution now points to an extragalactic origin for the cloud.<sup>2</sup> The computation suggests a disc crossing to have occurred at  $\sim 46 \text{ Myr}$  ago, at the less dense outer disc. Such a recent shock of the cloud with the disc together with its survival would imply that the cluster formation  $\sim 2 \text{ Myr}$  ago awaited cooling processes. Employing the second star in Table 2 the cloud would make a flyby along the Galaxy, but our simulation does not consider the deceleration by the drag of the ram pressure exerted by the halo. For the sake of emphasizing the role of uncertainties, we considered the case of null transverse velocity, since the first and



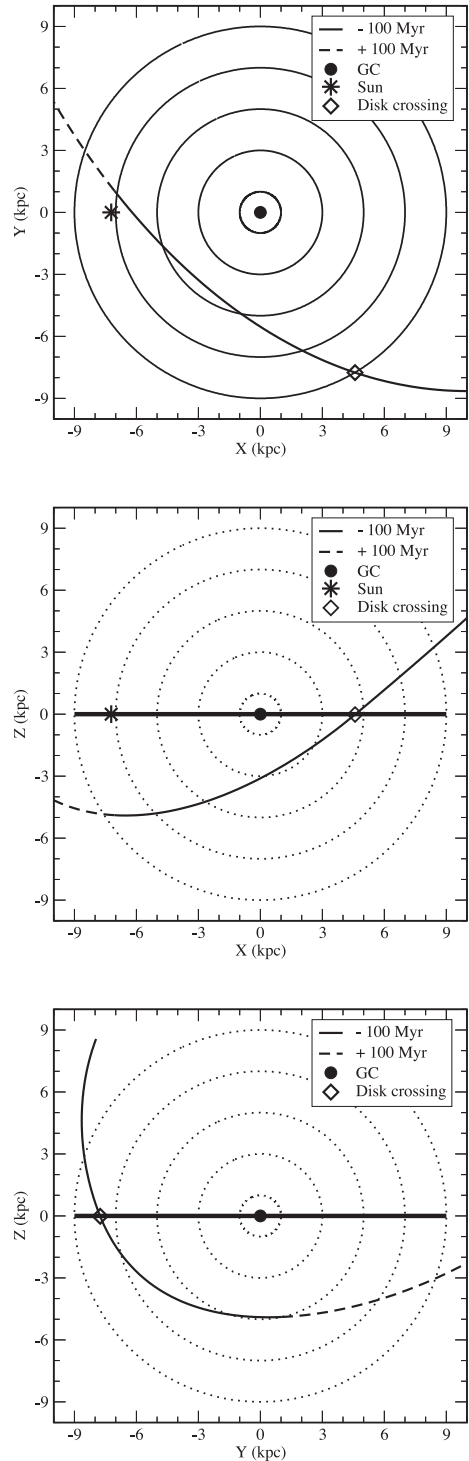
**Figure 5.** WISE W3 (10 arcmin  $\times$  10 arcmin) image of dust emission centred on C 438.

<sup>2</sup>For more definitive results we must await *GAIA* ([http://www.esa.int/Our\\_Activities/Space\\_Science/Gaia](http://www.esa.int/Our_Activities/Space_Science/Gaia)) proper motions.



**Figure 6.** Orbit of high-latitude cloud HRK 81.4–77.8 using  $V_{\text{LSR}} = -8 \text{ km s}^{-1}$ . Circles in the upper panel are distances in the Galactic  $X$ – $Y$  plane and in the middle and bottom panels radial distances on the vertical plane. The diamond indicates the disc crossing. The present cloud position is at the intersection of the solid and dashed lines. The Galactic disc is represented by the solid horizontal lines in the middle and bottom panels. This scenario favours a Galactic fountain model.

third stars in Table 2 have uncertainties of the order of the values. No UCAC4 counterpart was detected in C 438. We conclude that HRK 81.4–77.8 is clearly a key object for understanding the high latitude distribution of halo clouds.



**Figure 7.** Orbit of high-latitude cloud HRK 81.4–77.8 with  $V_{\text{LSR}} = -8 \text{ km s}^{-1}$  together with transverse velocity, considering two stars (first and third in Table 2) with proper motion in the area of the cluster C 439. Symbols as in Fig. 6. This scenario favours an extragalactic origin for the cloud.

The extragalactic clouds, especially the high velocity ones, may have in part origin in the tidal interaction between the Magellanic Clouds and the Galaxy (Olano 2004). The source of clouds in the SMC/LMC would be primarily tidal, while in the Galactic disc the Chimney effect may be significant. Violent star formation in

**Table 2.** Stars with UCAC4 proper motion in the direction of C 439.

Star designation	$\alpha(2000)$ (h m s)	$\delta(2000)$ ( $^{\circ}$ $'$ $''$ )	$\ell$ ( $^{\circ}$ )	$b$ ( $^{\circ}$ )	pmRA mas yr $^{-1}$	pmDE mas yr $^{-1}$	Other designation	Membership status
UCAC4 361-000 373	00:17:36.834	-17:48:13.42	081.2618	-77.8432	$5.2 \pm 1.9$	$2.1 \pm 2.0$	2MASS 00 173 683-1748 135	Member
UCAC4 361-000 371	00:17:31.560	-17:48:17.09	081.1810	-77.8309	$20.6 \pm 3.4$	$-20.7 \pm 3.2$	2MASS 00 173 155-1748 171	No member
UCAC4 361-000 366	00:17:26.087	-17:49:18.00	081.0503	-77.8307	$4.8 \pm 3.9$	$-4.0 \pm 6.9$	2MASS 00 172 608-1749 182	Member

the LMC and SMC will probably produce the Chimney effect. However, several hundred of massive stars in the disc are necessary to throw HRK 81.4–77.8 up to the present position, in the sense that multiple generations of star formation are required to develop a sequential supernovae event generating a continuous superwind (Normandeau et al. 1996; Oey et al. 2005; McClure-Griffiths et al. 2006). Winds from OB stars may also contribute. In this way, expanding superbubbles may trigger star formation generating multiple star-forming episodes renewing the fuel source needed for its own expansion and ejecting dust up even more distant (Dove, Shull & Ferrara 2000; Baumgartner & Breitschwerdt 2013). After loss of the pressure support the dust may rain on the disc forming a Galactic fountain.

#### 4 CONCLUDING REMARKS

We discovered by means of *WISE* two ECs that are located extremely far from the Galactic plane. The clusters appear to represent a star-forming event in the high-latitude low-velocity molecular/H I cloud HRK 81.4–77.8. We determined intrinsic and orbital parameters for the ensemble. As far as we are aware, this is the first detection of star formation in a high-latitude molecular cloud. The direct determination of distance for such a halo Galactic cloud is an unprecedented result.

Using *WISE* and 2MASS both ECs are  $\sim 2$  Myr old and are located at a distance from the Sun of  $\sim 5.1$  kpc. Adopting  $R_{\odot} = 7.2$  kpc we derive for C 439 an  $R_{GC} = 8.7 \pm 0.26$  kpc and spatial components  $x_{GC} = -7.05 \pm 0.02$  kpc,  $y_{GC} = 1.06 \pm 0.10$  kpc, and  $z_{GC} = -4.97 \pm 0.46$  kpc. C 438 presents  $R_{GC} = 8.7 \pm 0.4$  kpc and the spatial components  $x_{GC} = -7.04 \pm 0.02$  kpc,  $y_{GC} = 0.97 \pm 0.13$  kpc, and  $z_{GC} = -4.99 \pm 0.69$  kpc.

According to the derived parameters for the newly found ECs C 438 and C 439, HRK 81.4–77.8 is located at a distance from the Galactic Centre of  $\sim 8.7$  kpc and  $\sim 5.0$  kpc below the disc.

In short, HRK 81.4–77.8, C 438, and C 439 may be either falling on a ballistic trajectory towards the Galactic disc, or carrying out a twisted flyby across the halo.

Existing estimates of total or main-clump masses of intermediate-latitude clouds range from  $\sim 30$  to  $\sim 220 M_{\odot}$ , e.g. MBM 20 (LDN 1642), MBM 41-44, and MBM 55 (McGehee 2008; Malinen et al. 2014). Thus, our mass estimates for the ECs are comparable. Considering the molecular gas to star conversion efficiency of  $\sim 30$  per cent (e.g. Goodwin & Bastian 2006), our results imply that high-latitude clouds should be, typically, more massive than the intermediate-latitude counterparts. A possible reason is the cloud fragmentation by halo dragging forces. The determined distance and probable orbital behaviour place HRK 81.4–77.8 in the halo, at least an order of magnitude higher than intermediate-latitude clouds. Regarding C 438 and its location at the edge of the cloud, it might be similar to different clumps observed in intermediate-latitude clouds, such as MBM 41-44. Indeed, the  $100 \mu\text{m}$  map (Fig. 1) shows that HRK 81.4–77.8 hosts other dust clumps near the border as well.

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