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The outermost cluster of M 31*

S. Galleti[1,2], M. Bellazzini[2], L. Federici[2], and F. Fusi Pecci[2]

[1] Università di Bologna, Dipartimento di Astronomia, via Ranzani 1, 40127 Bologna, Italy
e-mail: silvia.galleti2@unibo.it
[2] INAF – Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy
e-mail: [michele.bellazzini;luciana.federici;flavio.fusipecci]@bo.astro.it

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Abstract. We report on the identification of a new cluster in the far halo of the M 31 galaxy. The cluster, named Bologna 514 (B514) has an integrated magnitude $M_V = -8.5 \pm 0.6$, and a radial velocity, as estimated from two independent low-resolution spectra, $V_{\rm r} = -456 \pm 23$ km s^{-1}, which fully confirms its membership to the M 31 system. The observed integrated spectrum is very similar to those of classical globular clusters. Being located at ≃4° (≃55 kpc in projected distance) from the center of the parent galaxy, B514 is by far the most remote M 31 cluster ever discovered. Its projected position, near the galaxy major axis, and M 31-centric velocity, similar to that observed in the outermost regions of the HI rotation curve, may indicate that it belongs to the subsystem of M 31 clusters that has been recently proposed (Morrison et al. 2004) to be part of the dynamically-cold thin disc of the galaxy.

Key words. galaxies: Local Group – galaxies: star clusters – galaxies: kinematics and dynamics – galaxies: spiral

1. Introduction

The globular cluster system of M 31 (the Andromeda galaxy) has been the subject of deep investigations since the dawn of extragalactic astronomy (Hubble 1932). M 31 is the only giant spiral galaxy beyond the Milky Way that we can hope to study in some detail, and globular clusters (GCs) are generally recognized as excellent tracers of the physical properties of the parent stellar system (Hodge 1992). The comparative study of the GC systems of M 31 and of the Milky Way may also provide very fruitful insights on the formation history of the parent galaxies as well as important constraint to theories of GC formation (see Harris 2001, and references therein). Finally, the kinematics of GC provides a classical tool to estimate the mass distribution of the parent galaxy out to large distances (see, Evans et al. 2003, and references therein, for the case of M 31).

For the above reasons, the observational effort to find out M 31 globulars and to measure their fundamental parameters has been large and extensive in the last 50 years (see, for example Vetešnik 1962; van den Bergh 1967, 1969; Baade & Arp 1964; Sargent et al. 1977; Crampton et al. 1985; Battistini et al. 1980, 1982, 1987, 1993; Sharov et al. 1995; Mochejska et al. 1998, and references therein) and is still continuing (Barmby et al. 2000, 2001; Perrett et al. 2002; Galleti et al. 2004a). The quest for clusters located at large projected distances from the center of the galaxy is of particular relevance since these object would allow new insight into unexplored regions of M 31 and they would provide the maximum "leverage" to constrain the mass distribution of the galaxy (see, for example Federici et al. 1993; and Evans et al. 2003, and references therein).

In this framework, we have recently started a programme aimed at the identification of new candidate globular clusters and at the confirmation of known candidates in the outermost regions of M 31. During a pilot observational project we took low resolution spectra ($\frac{\Delta\lambda}{\lambda} \sim 1300$) of two promising candidates selected from the Extended Source Catalogue of 2MASS (XSC, Cutri et al. 2003). One of them turned out to be a genuine M 31 cluster, by far the most distant from the center of the galaxy that has been ever identified. In the present contribution we briefly report on this new finding.

In the following we will adopt the distance modulus of M 31 from McConnachie et al. (2005), $(m-M)_0 = 24.47$ (see also Durrell et al. 2004), the average color excess $E(B-V) = 0.11$, from Hodge (1992), and the line of sight systemic velocity of $V_{\rm r} = -301$ km s^{-1}, from van den Bergh (2000). All the parameters for known M 31 globulars are from the comprehensive compilation by Galleti et al. (2004a) with the only exception of radial velocities and spectroscopic metallicity estimates that are drawn from Perrett et al. (2002), when possible, and from Huchra et al. (1991) when lacking in the former list. All over the paper we will only consider GC candidates whose nature has been confirmed by means of spectroscopy and/or high resolution imaging (confirmed clusters, see Galleti et al. 2004a, and references therein), if not otherwise stated.

* Based on observations obtained with the Cassini Telescope at the Loiano Observatory (Italy), operated by INAF – Osservatorio Astronomico di Bologna.

Table 1. Observed parameters of the targets.

2MASS ID	RA(J2000)	Dec(J2000)	r	J	H	K	V_r [km s^{-1}] Nov.	V_r [km s^{-1}] Jan.
2MASX-J00310983+3753596	$0^h31^m9.8^s$	37°53′59.6″	5.4″	14.272 ± 0.048	13.607 ± 0.059	13.661 ± 0.087	−459 ± 12	−453 ± 29
2MASX-J00262028+4400377	$0^h26^m20.3^s$	44°00′37.7″	6.6″	14.122 ± 0.042	13.430 ± 0.057	13.184 ± 0.061	20 069 ± 22	20 097 ± 76[1]
							20 058 ± 21	

r is the Kron circular aperture radius in the J band (see Cutri et al. 2003, for details); J, H and K integrated magnitudes are derived as in Galleti et al. (2004a). [1] From a spectrum obtained with a slit of 2″, see text.

2. Selection of distant candidates

In Galleti et al. (2004a, hereafter G04) we provided J, H and K integrated magnitudes of 693 candidate M 31 GCs obtained from the All Sky Data Release of 2MASS. Of the 279 confirmed clusters included in this set, the large majority (258) were found in the Point Source Catalogue (PSC) of the survey, while just 21 were included in the XSC. This strongly suggest that if a M 31 GC candidate is included in the XSC it is a bona-fide extended source, i.e. it is not a foreground stars[1]. Intrigued by this possibility we searched for new GC candidates among XSC sources within a ∼9° × 9° area centered on M 31 (and excluding the innermost 3° × 3° field already studied in G04). Using suitable combinations of the structural parameters provided in the XSC (ellipticity, radius, etc., see Galleti et al. 2004b for some examples of the adopted techniques) we selected 49 candidates worth of further investigation. DSS-2 images of these candidates were visually inspected and 19 of them were rejected as obvious galaxies during this phase. As a pilot project we decided to take spectra of the two most promising candidates (as judged from their appearance on DSS-2 images), whose 2MASS names and main characteristics are reported in Table 1.

2.1. Observations

We obtained 5 low-resolution integrated-light spectra of the two candidates globular clusters. The observations were performed in November 16−17, 2004 and January 02−05, 2005, with the BFOSC[2] spectrograph operated at the 1.52 m Cassini Telescope of the Loiano Observatory, near Bologna (Italy). The detector was a thinned, back illuminated EEV CCD, with 1300 × 1340 px^2. During the first night of the January run a slit of 2″ was used to match poor seeing conditions. A slit of 1.5″ was used during the other nights. As a consequence, the instrumental resolution was slightly lower during the first night of the January run. The adopted set-up (slit width 1.5″) provides a spectral resolution $\Delta\lambda = 4.1$ Å over the range 4200 Å $< \lambda <$ 6600 Å. The pixel scale is 1.94 Å px^{-1}. We took a He-Ar calibration lamp spectrum after each scientific exposure, maintaining the same pointing of the telescope. In the November run we obtained two spectra of 2MASX-J00262028+4400377 and one of 2MASX-J00310983+3753596; in the January run we took one spectrum for each object (the spectrum of 2MASX-J00262028+4400377 was observed with the slit of 2″). The exposure time was 2700 s for each target spectrum, with a characteristic signal-to-noise ratio $S/N \sim 25$. During each observing night we also observed, with the same set-up, four template targets that we adopted as radial velocity standards: the M 31 globular clusters B158 and B225 (heliocentric radial velocities from Perrett et al. 2002) and the two stars HD 12029, HD 23169 (heliocentric radial velocities from the SIMBAD database). In the first night of the January run only B225 was observed as template with the slit of 2″. All the template spectra have $S/N > 70$.

All the scientific spectra were processed with standard reduction techniques in IRAF. In summary, after subtracting a masterbias, all frames were divided by a normalized flat-field image. Subsequently, the IRAF/twodspec procedures were used to sky-subtract, extract and calibrate in wavelength all spectra. The heliocentric radial velocities (V_r) of the candidates globular clusters were obtained by cross-correlation (CC) with the high S/N spectra of the templates, using the IRAF/fxcor package (see Tonry & Davis 1979, for details of the technique).

The obtained solutions were unambiguous in all cases, i.e., a well defined single peak of the CC function was found, with heights in the range $0.3 \leq CC \leq 0.55$; the typical uncertainty on the single estimate is ∼50 km s^{-1} (*FWHM* of the CC peak). For each of our target spectra we took the average of the V_r estimates from the different templates (except for the spectrum of 2MASX-J00262028+4400377 taken in the January run, for which only one template spectrum was obtained with the 2″ slit setup). The standard deviations of these estimates were summed in quadrature with the errors in the velocity of the templates to obtain the uncertainty on the V_r from each single spectrum. The V_r estimates obtained in this way from the spectra of the same target taken in different nights were fully compatible among each other, within the uncertainties. Hence we took the average of the V_r obtained from the different spectra (nights) as our final estimate of the heliocentric radial velocity. The final total uncertainty was obtained by averaging the uncertainties from the (two-three) independent estimates. As a consistency test we derived the velocity of each template

[1] Foreground Galactic stars are the major source of false M 31 GC candidates, together with background galaxies. However the nature of the latter can be firmly established just on the basis of their radial velocity that shall be much higher than the systemic velocity of M 31, while a foreground stars cannot be always identified on the basis of its velocity alone.

[2] See `http://www.bo.astro.it/~loiano/TechPage/pagine/BfoscManualTechPage/BfoscManual.htm` for further details on the instrument.

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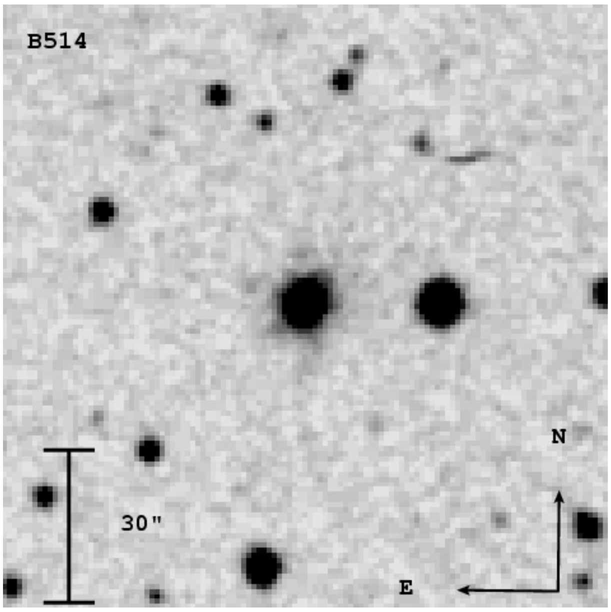

Fig. 1. 2′ × 2′ DSS-II(Red) image centered on B514 (`http://archive.eso.org/dss/dss`). Note the fuzzy nature of the B514 image with respect to the nearby bright star located ∼20″ to the West of the cluster.

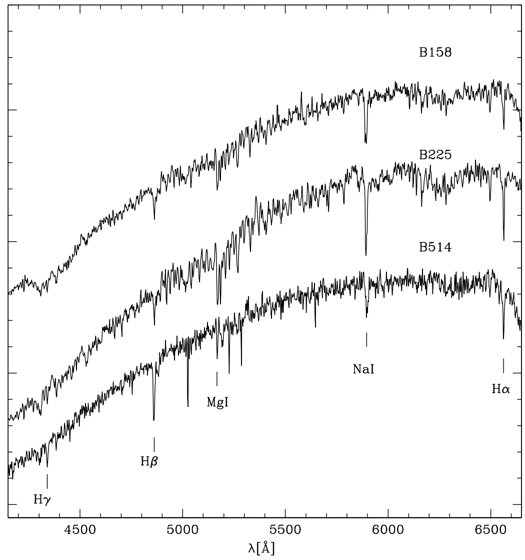

Fig. 2. Spectra of the confirmed M 31 globular clusters B225, B158 compared with that of B514. The most relevant spectral features are marked, as a reference. The ordinate axis is in arbitrary units. The spectra are corrected for the heliocentric radial velocity (e.g. shifted to rest-frame).

cluster by CC with the others templates and in both case we obtained estimates within ±2.0 km s^{-1} of the published values (Perrett et al. 2002).

The observed parameters of our targets are shown in Table 1. The very high velocity reveals that 2MASX-J00262028+4400377 is clearly a background galaxy at $z \simeq 0.07$. On the other hand 2MASX-J00310983+3753596 has a velocity within ∼150 km s^{-1} of the systemic velocity of M 31 (the straight velocity dispersion of M 31 GCs is ≃160 km s^{-1}) hence it can be safely classified as a confirmed M 31 cluster. Following the naming convention by Battistini et al. (1987) we christen the newly discovered cluster Bologna 514 (B514). The object appears clearly non-stellar even in DSS-2 images (Fig. 1) and has a spectrum typical of known Andromeda GCs (see Fig. 2). The main derived parameters for B514 are reported in Table 3. No matching counterpart has been found in the NED and SIMBAD databases, except for the obvious 2MASS entry. In addition, other databases such as Vizier (Ochsenbein et al. 2000) were consulted. We found that B514 is listed in the HYPERLEDA catalogue (Paturel et al. 2003) as an extended source detected on the DSS (PGC2112471), lacking any information on the velocity.

While this contribution was near to completion we realized that one of the new M 31 GC candidates found by Huxor et al. (2004) has a position similar to B514 (according to their Fig. 1, since they don't provide the coordinates or the radial velocity estimates for the presented candidates). Upon direct request, these authors kindly confirmed that their outermost candidate is indeed the same object we are dealing with in the present contribution (Huxor et al., private communication). Hence B514 has been independently identified also by this team. It is worth noting that in the image reported as Fig. 3 of Huxor et al. (2004), the object clearly appears as a partially resolved stellar system.

3. Bologna 514: The most remote M 31 cluster

The 2MASS NIR integrated magnitudes of B514 indicates that it is a quite luminous object, e.g. among the ∼40% brightest M 31 GCs in K band in the extensive database by G04. As a reference for future observations it may be useful to provide a guess of the visual integrated magnitude. Lacking any visual photometry, we obtained a rough estimate of the V integrated magnitude by fitting the linear relations between V and J, H, K magnitudes for the confirmed clusters of M 31, taken from the G04 catalogue:

$$V = 0.81J + 4.70 \text{ (rms = 0.46 mag)}$$

$$V = 0.71H + 6.62 \text{ (rms = 0.49 mag)}$$

$$V = 0.79K + 5.50 \text{ (rms = 0.56 mag).}$$

We obtained $V = 16.26 \pm 0.46, 16.28 \pm 0.50, 16.29 \pm 0.57$ from the V vs. J, V vs. H and V vs. K relations, respectively. As a final conservative estimate we take $V = 16.3 \pm 0.5$. With our distance and reddening assumptions this corresponds to an absolute integrated magnitude $M_V = -8.5 \pm 0.6$, that places B514 among the ∼30% most luminous clusters of M 31 also in the V band (G04).

The most remarkable characteristic of the clusters is its position within the M 31 system. B514 is located at $R \simeq 4°$ from the center of the galaxy, corresponding to a projected distance R_p = 54.7 kpc, hence it is by far the most distant M 31 cluster presently known. The previous "record holder" (G 1 = Mayall II, see Meylan et al. 2001), lies at $R \simeq 2.5°$ (R_p = 34.2 kpc). Most interestingly, the cluster lies just ≃14′

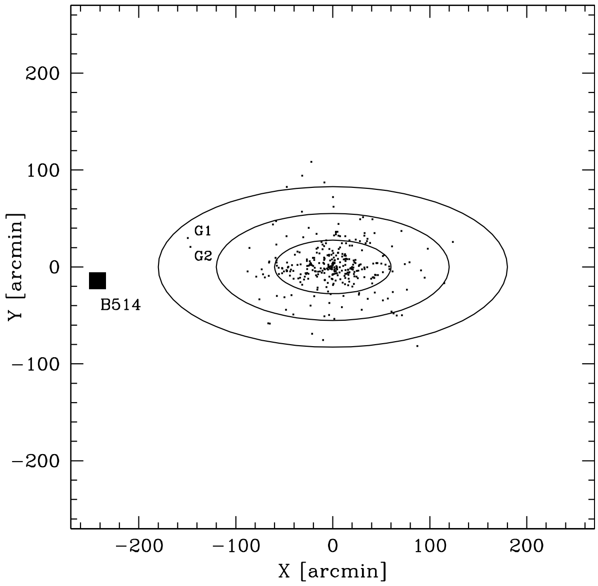

Fig. 3. Distribution of M 31 GCs (small dots) in the X, Y plane (distances from the center of the galaxy projected along the major and minor axis, respectively). Ellipses with the same axis ratio as the apparent disc of M 31 and semi-major axis of 1°, 2°, and 3° are overplotted, for reference. The most distant clusters (G1 and G2) and the new object B514 (filled square) are labeled.

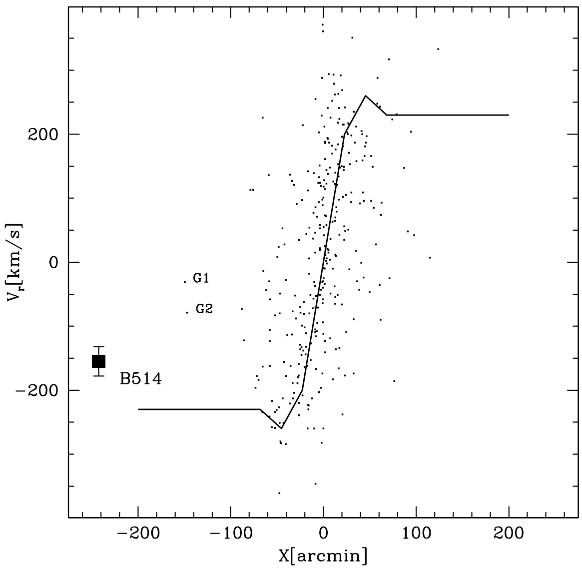

Fig. 4. Radial velocity of the M 31 globular clusters (corrected for the systemic velocity of M 31) vs. the projected distance along the major axis (X). The HI rotation curve of the galaxy (from van den Berg 2000) is plotted as a continuous line.

apart of the galactic major axis, on the south-western ideal extension of the disc (see Fig. 3). Moreover its "M 31-centric" line-of-sight velocity ($V_{M31} = -155 \pm 23$ km s^{-1}) places it around the extrapolation at large distance of the HI disc velocity curve (see Fig. 4).

Table 2. Line indices for the observed M 31 clusters.

Id.	H_β	*Mgb*	H_β [BH]	*Mgb* [BH]
(1)	(2)	(3)	(4)	(5)
B158	0.084	0.092	0.085	0.089
	±0.008	±0.008	±0.006	±0.007
B225	0.053	0.128	0.071	0.130
	±0.008	±0.007	±0.003	±0.002
B514	0.118	0.030	–	–
	±0.011	±0.010	–	–

All the indices are expressed in magnitudes. Columns (2) and (3) report the estimates we obtained from our spectra, Cols. (4) and (5) report the estimates published by Brodie & Huchra (1990, BH). The indices are defined as in BH.

Table 3. Derived parameters for Bologna 514.

	B514
M_V	−8.5 ± 0.6
X	–242.40′
Y	–14.16′
R	242.81′
R_p	55.3 kpc
V_r	−456 ± 23 km s^{-1}
[Fe/H]	−1.8 ± 0.3

3.1. Metallicity and age

To have an indication of the average metal content we used the relation between [Fe/H] and $(J-K)_0$ provided by Barmby et al. (2000). Adopting $(J-K)_0 = 0.55 \pm 0.10$ for B514 (see Table 1) we obtain [Fe/H] $= -2.0 \pm 0.9$, suggesting that the cluster is quite metal poor (at least if its age is similar to that of the other M 31 GCs). As a comparison, we used the same relation for the clusters G 1 and G 2, that are also located at large distances from the center of M 31 and for which spectroscopic estimates of the metallicity are available in the literature (see Sect. 3.1 for further discussion about these clusters in relation with B514). According to G04, G 1 has $(J-K)_0 = 0.75 \pm 0.10$ from which we obtain [Fe/H] $= -0.8 \pm 0.9$, in good agreement with the estimates by Huchra et al. (1991) and Meylan et al. (2001) who find [Fe/H] $= -1.08 \pm 0.09$ and [Fe/H] $= -0.95 \pm 0.09$, respectively; G 2 has $(J-K)_0 = 0.62 \pm 0.10$, corresponding to [Fe/H] $= -1.6 \pm 0.9$, in good agreement with [Fe/H] $= -1.70 \pm 0.36$ by Huchra et al. (1991).

3.1.1. Line indices

We have measured the line indices H_β and *Mgb* from our spectra of M 31 GCs (B158, B225 and B514), according to different definitions (Brodie & Huchra 1990; Perret et al. 2002; and Trager et al. 1998). The obtained estimates in the scale by Brodie & Huchra (1990) are reported in Table 2 together with the values published by the same authors for B158 and B225. In all the considered cases the agreement of our estimates with the measures available in the literature for these clusters is very good. We choose the H_β and *Mgb* indices because (a) they are quite sensitive to age and metallicity, respectively (see, for example, Buzzoni 1995, and references therein) and (b) they

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correspond to rather strong features in our spectra, thus they can be reliably measured.

Adopting the [Fe/H] vs. *Mgb* calibration by Perret et al. (2002) we find [Fe/H] = −1.85 ± 0.3 for B514; with the analogous relation provided by Brodie & Huchra (1990) we obtain [Fe/H] = −1.79 ± 0.3. As a final metallicity we take the average of the two [Fe/H] = −1.8 ± 0.3, in good agreement with the photometric estimate derived above. The fraction of M 31 GCs with [Fe/H] ≤ −1.5 among the confirmed clusters having spectroscopic metallicity estimates is 36% (G04), hence B514 is in the low metallicity tail of the distribution. However metal poor GCs are more abundant in the outer regions of M 31 (see Perrett et al. 2002), therefore the metallicity of B514 is not unusual given its location.

Finally, comparing the measured indices with the predictions of the theoretical models of Buzzoni (1989) and with the values observed in well studied galactic globulars (Brodie & Huchra 1990) we find that B514 has H_β and *Mgb* values typical of metal-poor clusters with age larger than 10 Gyr. Hence the available photometric and spectroscopic data strongly indicates that B514 is a classical old and metal-poor globular cluster.

3.2. Discussion

The newly identified B514 cluster is placed in the realm of distances inhabited by the dwarf galaxy satellites of M 31 (see Mateo 1998) but it doesn't lie in the surroundings of any of them, neither appears superposed to the various low-surface-brightness structures and/or streams discovered in recent surveys (see, for example, Ibata et al. 2001, 2004; Zucker et al. 2004a, 2004b; Merrett et al. 2003, and references therein).

On the other hand, several authors have proposed that the stellar population of the Andromeda galaxy (as sampled from Earth-centered line of sights) is dominated by an extended disc component that provides the large majority of the sampled stars out to $R_\mathrm{p} \simeq 35$ kpc (Sarajedini & Van Duyne 2001; Ferguson & Johnson 2001; Worthey et al. 2004). Moreover, Morrison et al. (2004) showed that, at odds with the case of the Milky Way, a significant fraction of M 31 GCs share the positional and kinematical properties of the dinamically-cold thin disc of the galaxy. Figures 3 and 4, above, shows that the position and M 31-centric velocity of B514 are fully compatible with the hypothesis that the cluster belongs to the Morrison et al.'s thin disc clusters. If this will be confirmed by further observations it would imply a really huge size for the M 31 disc, with far reaching consequences on our ideas on the formation and evolution of galactic discs.

Finally, it appears as a curious coincidence that the tree most remote M 31 clusters known (e.g. B514, G1 and G2, see Figs. 3 and 4) are all located in the proximity of the major axis and on the same side of the galaxy (but B514 is more than 1° farther than the other two; see also Sect. 3.1 for dicussion about the metallicity). While their M 31-centric l.o.s. velocities differ by more than 100 km s^{-1} they are all negative, e.g. in agreement with the sign of the rotation pattern of M 31. Since projection effects may have a significant rôle in producing the observed differences in position and velocity, the possibility that the three systems may be somehow related (as, for instance, by sharing similar orbits) cannot be excluded at present and deserves further investigation.

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