The distance to the young cluster NGC 7129 and its age

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ABSTRACT
The dust cloud TGU H645 P2 and embedded in it young open cluster NGC 7129 are investigated using the results of medium-band photometry of 159 stars in the Vilnius seven-colour system down to $V = 18.8$ mag. The photometric data were used to classify about 50% of the measured stars in spectral and luminosity classes. The extinction $A_V$ vs. distance diagram for the 20' × 20' area is plotted for 155 stars with two-dimensional classification from the present and the previous catalogues. The extinction values found range between 0.6 and 3.4 mag. However, some red giants, located in the direction of the dense parts of the cloud, exhibit the infrared extinction equivalent up to $A_V = 13$ mag. The distance to the cloud (and the cluster) is found to be 1.15 kpc (the true distance module 10.30 mag). For determining the age of NGC 7129, a luminosity vs. temperature diagram for six cluster members of spectral classes B3 to A1 was compared with the Pisa pre-main-sequence evolution tracks and the Palla birthlines. The cluster can be as old as about 3 Myr, but star forming continues till now as witnessed by the presence in the cloud of many younger pre-main-sequence objects identified with photometry from 2MASS, Spitzer and WISE infrared surveys.

Key words: stars: fundamental parameters – ISM: dust, extinction, clouds: individual: TGU H645 P2 – Galaxy: open clusters and associations: individual: NGC 7129

1 INTRODUCTION
A small group of early-type stars surrounded by the reflection nebula NGC 7129 was described by Herbig (1960), in his pioneering paper on the search of emission-line B and A stars associated with nebulosities. Later on, more fainter stars in the nebula and around it were identified by Strom et al. (1976), Hartigan & Lada (1985), Hodapp & Mannings (1994). The cluster was included in the catalogue of infrared star clusters and stellar groups by Bica, Dutra & Barbule (2003). The dust cloud, now known as TGU H645 P2 (Dobashi et al. 2005), is illuminated mainly by the three hot stars: BD+65 1637 (B2e, $V = 10.15$), BD+65 1638 (B3, $V = 10.18$) and LKhr 234 (B6e, $V = 11.90$); the 1st and the 3rd of them are the Herbig Ae/Be stars (Herbig 1960). Most fainter stars of the cluster are also young stellar objects (hereafter YSOs) identified by Magakian et al. (2004) using spectral observations and VRI photometry, and by Gutermuth et al. (2004, 2005), Muzerolle et al. (2004), Stelzer & Scholz (2009) using 2MASS and Spitzer infrared photometry and Chandra X-ray survey. Kato et al. (2011) identified some possible YSOs in the close vicinity of LKhr 234 with high-resolution near IR images. For a few YSOs in the cluster and in the dark cloud LDN 1181 located about 0.5° north of NGC 7129, masses, spectral types, emission-line intensities, $BVRI$ photometry, spectral energy distributions and physical parameters were obtained by Kun et al. (2009). A review of the investigations of NGC 7129 and its individual objects was published by Kun et al. (2008).

The distance determinations to NGC 7129 are scarce and of low accuracy. The first distance estimation was done by Racine (1968), who used one-dimensional spectral classes of the stars BD+65 1637 and BD+65 1638 (B2nne and B3) and their $UBV$ photometry. The distance moduli 12.2 (2.75 kpc) and 10.0 (1 kpc) were estimated, but they are very uncertain, since the luminosity classes of these stars were unknown. The last of these two distance values has been used in most subsequent investigations, including the recent papers in the Spitzer era. The next estimate of the distance to the NGC 7129 complex, 1.26 kpc, was published by Shevchenko & Yakubov (1989) using $BV$ photometry and spectral classification of a few reddened stars. However, their result is also of low accuracy since the authors have used one-dimensional spectral classes estimated visually from low-dispersion objective prism spectra. Thus, NGC 7129 remains one of the rare NGC ob-

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2 OBSERVATIONS, THEIR PROCESSING AND RESULTS

Fig. 1 shows the $13' \times 13'$ area with the NGC 7129 cluster in the centre ($21^h 43^m 00^s$, $+66^\circ 06'$. In 2009 October this area was observed with the 1.8 m VATT telescope on Mt. Graham in Arizona with a CCD camera and seven filters of the Vilnius photometric system. The exposure lengths were from 800 to 20 seconds in the two ultraviolet filters and from 100 to 4 seconds in the remaining filters. The number of exposures used was 86. The magnitudes determined from multiple exposures in the same filter were averaged. More details about the observations, their processing and the classification of stars are given in Paper II.

In this area, 159 stars down to $V = 18.8$ mag were measured. The distribution of the observed stars in apparent magnitudes is shown in Fig. 2. Magnitudes and colours for the stars are listed in Table 1. The columns list the following information: star number, equatorial coordinates J2000.0, magnitude $V$, colour indices $U-V$, $P-V$, $X-V$, $Y-V$, $Z-V$ and $V-S$, photometric spectral types in the MK system, and flags to the notes placed at the end of the table. The rounded coordinates of stars were taken from the PPMXL catalog (Roeser et al. 2010). The finding chart for the measured stars in the NGC 7129 area is given in Fig. 3.

The r.m.s. errors of the magnitudes $V$ and colour indices $X-V$, $Y-V$, $Z-V$ and $V-S$ to $V = 16$ mag usually are lower than 0.02 mag, the errors of $U-V$ and $P-V$ are about 1.5–2.0 times larger. At $V = 17.5$ mag the accuracy of photometry in the ultraviolet, especially for heavily reddened stars, is too low for a reliable classification of stars. For most of these stars the $U-V$ and $P-V$ colour indices are not given. Colour indices with $\sigma = 0.05–0.10$ mag are marked with colons. Most of these stars are either fainter than 18 mag or are known as YSOs.

Single asterisks in the last column signify YSOs for which the notes are given at the end of the table. Most YSOs have been discovered by Hz emission, by infrared excesses or by X-ray emission in the papers described in the Introduction. Some YSOs were identified in the present investigation using the $K_s-[3.4]$ vs. $[3.4]-[4.6]$ diagram which combines the 2MASS and WISE magnitudes. The calibration of this diagram in YSO classes was taken from

![Figure 1.](image1.png)

Figure 1. Area of the cluster NGC 7129 observed in the Vilnius photometric system with VATT ($13' \times 13'$). The $2' \times 2'$ square surrounds a group of stars which was suspected by Bica et al. (2003) as an infrared cluster. More about this group see in Section 7. The DSS2 Red map from SkyView.

![Figure 2.](image2.png)

Figure 2. Distribution of the measured stars in the NGC 7129 area in apparent magnitudes. The shadowed parts of the columns correspond to stars for which two-dimensional spectral types were determined.

1 The mean wavelengths of the passbands are 345 ($U$), 374 ($P$), 405 ($X$), 466 ($Y$), 516 ($Z$), 544 ($V$) and 656 ($S$) nm. For more details about the system see in the monograph Straižys (1992), available in the pdf format from //http://www.itpa.lt/MulticolorStellarPhotometry/
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Figure 3. Finding chart for the measured stars in the NGC 7129 area. The star numbers are written on a DSS2 Red image from SkyView.

Koenig et al. (2012). Variable stars in the area were identified using the Catalogue of variable stars in open cluster fields by Zejda et al. (2012). The stars found to be binaries or having asymmetric images were not classified in luminosity classes – in the last column they are designated by double asterisks.

3 INTERSTELLAR REDDENING LAW AND PHOTOMETRIC CLASSIFICATION

From the Vilnius photometric data, spectral and luminosity classes in the MK system were determined for 72 stars (Table 1 and Fig. 2). The classification method was based on the interstellar reddening-free $Q$-parameters and intrinsic colour indices, more information is given in Papers I and II. In Table 1 spectral classes are designated in the lower-case letters to indicate that they are determined from photometric data. In calculating interstellar reddening-free $Q$-parameters and in dereddening colour indices, the normal interstellar reddening law was applied. Its normality was verified with the $J - H$ vs. $H - K_s$ diagram (Fig. 4) plotted for the NGC 7129 area which contains stars with very different reddenings.

The area, from which the stars are plotted in Fig. 4, is of the $15\arcmin \times 15\arcmin$ size, with the center on NGC 7129. Lower than $J - H = 1.5$ the lower accuracy limit of magnitudes, < 0.1, is accepted. The main sequence (MS, brown belt), red giant branch (RGB, orange belt), the intrinsic locus of red clump giants (RCG) with its reddening line, and the intrinsic T Tauri line are shown. Open circles designate the YSOs from Table 1 and from the literature. The six B3–A1 stars, used in Section 6 for the age determination, are identified.

Figure 4. The $J - H$ vs. $H - K_s$ diagram for 2MASS stars with errors of magnitudes $\leq 0.05$ mag in the $15\arcmin \times 15\arcmin$ box centered on NGC 7129. Above $J - H = 1.5$ the lower accuracy limit of magnitudes, $< 0.1$, is accepted. The main sequence (MS, brown belt), red giant branch (RGB, orange belt), the intrinsic locus of red clump giants (RCG) with its reddening line, and the intrinsic T Tauri line are shown. Open circles designate the YSOs from Table 1 and from the literature. The six B3–A1 stars, used in Section 6 for the age determination, are identified.

The giants with $J - H > 1.5$ are listed in Table 2. Accepting that all these stars are RCGs, we calculated for them the extinctions $A_{K_s}$ and $A_V$, and distances with the equations

$$A_{K_s} = 2.0E_{H-K_s} = 2.0[(H - K_s) - 0.09],$$

$$5 \log d = K_s - M_{K_s} + 5 - A_{K_s},$$

$$A_V = 8.3 A_{K_s},$$

with $M_{K_s} = -1.6$ and $d$ in pc.

4 INTERSTELLAR EXTINCTION

Since the cluster NGC 7129 is embedded in the dust cloud, for the determination of the cluster distance we have applied the method which uses the rise of extinction of the field stars located at a distance of the dust cloud.

Interstellar extinctions were calculated with the equation

$$A_{K_s} = 2.0E_{H-K_s} = 2.0[(H - K_s) - 0.09],$$

$$5 \log d = K_s - M_{K_s} + 5 - A_{K_s},$$

$$A_V = 8.3 A_{K_s},$$

with $M_{K_s} = -1.6$ and $d$ in pc.
A_V = 4.16 [(Y - V)_obs − (Y - V)_c],

(4)

where the intrinsic colour indices (Y - V)_c for different spectral and luminosity classes were taken from Straižys (1992). Distances to stars were calculated with the equation

5 log d = V - M_V + 5 - A_V,

(5)

the absolute magnitudes M_V were taken from Straižys (1992), with a correction of -0.1 mag, adjusting the M_V scale to the distance modulus of the Hyades, V - M_V = 3.3 mag (Perryman et al. 1998).

For the determination of the extinction run with distance in the direction of NGC 7129, 72 stars from Table 1 with the most accurate spectral types were used. This sample was supplemented with 83 stars classified with good accuracy in Paper I and located outside the 13' × 13' area but inside the 20' × 20' area centered on the cluster. This area covers the whole molecular cloud around NGC 7129 shown in the CO map by Ridge et al. (2003). The known YSOs and other stars with low classification accuracy were excluded.

Fig. 5 shows the extinctions A_V plotted as a function of the distance d. The crosses designate the six cluster members of the highest luminosity. These stars will be discussed in Section 6. The error bar in distance corresponds to ΔM_V = ±0.5 mag, a typical 3σ error of absolute magnitudes estimated from photometric spectral types. The errors of A_V, originating from the observational errors and intrinsic ‘cosmic dispersion’ of the relation between Y - V and spectral classes, are of the order of ± 0.2 mag.
5 CLOUD DISTANCE

The distribution of stars in Fig. 5 shows that the extinction increases steeply close to \( d = 1 \) kpc where the TGU H645 P2 cloud can be located. The scatter of \( A_V \) at greater distances is quite large – from about 1 mag to 3.4 mag. Another, much lower rise of extinction up to 1 mag might be present at a distance of \( \approx 500 \) pc.

For determining the cloud distance we must take into account that a portion of stars are scattered toward lower distances because of negative distance errors. The main source of distance errors is in their absolute magnitudes – in the photometric classification we take \( \pm 0.5 \) as the 3\( \sigma \) error of \( M_V \). In this case the stars with the maximum negative distance errors will appear closer to the Sun by a factor of 1.26. Thus, if we find stars with large extinctions at a distance \( d_1 \) pc, the true distance of the cloud should be at \( d = 1.26 d_1 \). In Fig. 5 the mean distance of five considerably reddened stars \( (A_V > 1.4 \) mag) at \( d < 1.0 \) kpc is 0.91 kpc. If these stars are moved from the dust cloud shortward because of absolute magnitude errors, the front edge of the cloud is expected to be located at \( d = 1.15 \) kpc, which corresponds to the true distance modulus \( V-M_V = 10.30 \pm 0.17 \) mag. This r.m.s. error of \( V-M_V \) corresponds to the distance errors from \(-84\) pc to \(+91\) pc. At a distance of 1.15 kpc the angular diameter of the cloud, 0.3”, is equal to 6 pc.

Also, for the shortward scattering of apparent distances the unresolved binary stars can be responsible. If both components of a binary star are of the same luminosity, its real distance should be at 1.41 \( d_1 \). In this case the distance of the cloud should be at \( d = 1.28 \) kpc. Since we have no information that any of the five stars with apparent distances \( < 1 \) kpc is a binary, we will accept that their shifts shortward are due to the errors of \( M_V \) only.

As shown in Fig. 2, most stars in the NGC 7129 area with two-dimensional spectral types fall on 17–18 mag. The majority of them are main-sequence stars of spectral classes F and G. The two broken curves in Fig. 5 demonstrate the effect of limiting magnitude for F5 V stars with magnitudes \( V \) at 17 and 18. Above the upper curve only B- and A-type stars, as well as G–K–M giants can be found. These types of stars in this area are rare.

Fig. 5 shows that behind the dust cloud at 1.15 kpc the extinction does not increase – it remains approximately between 1.5 and 3.4 mag up to 4.5 kpc. This is expected, since at the Galactic latitude 9° our line of sight at 2 kpc reaches 320 pc above the Galactic plane, where dust clouds are quite rare. However, the \( J-H \) vs. \( H-K_s \) diagram of 2MASS shows (Fig. 4 and Table 2) that the background RCGs, located at distances from 3 to 8 kpc, are affected by reddening, which corresponds to \( A_V \) up to \( \approx 14 \) mag. The most reddened 11 RCGs with \( J-H > 1.5 \) are all seen mostly in the eastern (left) half of the cloud area with the largest dust density. The presence among them of a few ordinary K–M giants will not change the conclusion that the total extinction, created by the cloud in some directions, is as large as 10–14 mag.

6 HR DIAGRAM

Since the cluster NGC 7129 is embedded in the dust cloud TGU H645 P2, we accept the same distance both for the cloud and the cluster. We have identified only six stars close to the ZAMS for which the membership to the complex is evidenced by illumination of the surrounding dust and forming the reflection nebulae. Three of these stars, Nos. 96, 105 and 154, are 4–6’ away from the central concentration of visible and infrared objects. However, they all are located in the same dust and molecular cloud, and we will consider these three stars as the cluster members formed in the local condensations of gas and dust a few million years ago. The most active star formation continues up to now in the core of the cluster which, according to Gutermuth et al. (2004, 2005), has a diameter of \( 3' \), while the whole area in which YSOs are observed is about four times larger. Our further study of the cluster will be based only on these six stars which are massive enough to be located in the temperature vs. luminosity diagram close to the main sequence. We recognize them as cluster members only because they illuminate the surrounding dust cloud or are Herbig Ae/Be stars. Other cluster members are low-mass YSOs which have been easily recognized by their emission lines, infrared excesses and X-ray emission (see the Introduction). However, within 6’ from the cluster center we have not found more A or F stars whose distances would be close to 1.15 kpc. This means that during the last 1–3 Myr no more massive stars have been formed.

The data for the six cluster stars are given in Table 3. Fig. 6 shows the plot of these stars in the the log \( \frac{L}{L_\odot} \) vs. log \( T_{\text{eff}} \) diagram. Their luminosities in solar units were calculated with the equation

\[
\log \frac{L}{L_\odot} = 0.4(M_{\text{bol,}\odot} - M_{\text{bol,}\star}) = 0.4(4.72 - V + A_V + 10.30 - BC),
\]

where \( V \) is the apparent magnitude of the star, \( M_{\text{bol,}\odot} \) is its absolute bolometric magnitude, \( M_{\text{bol,}\star} = 4.72 \) is the bolometric absolute magnitude of the Sun, \( BC \) are the bolometric corrections, and 10.30 is the true distance modulus of the cluster. The extinctions \( A_V \) were determined with Eq. (4).

The three brightest stars in the cluster are BD+65 1637 (Herbig Ae/Be star), BD+65 1638 (YSO of Class III) and LkHα 234 (also Herbig Ae/Be star). To calculate the \( V_0 = V - A_V \) and \( (Y-\)
were calculated using the average magnitudes 0.71 and 1.48 mag, respectively. Their positions in Fig. 6 were calculated using the average magnitudes and B-V colours from Herbst & Shevchenko (1999). For BD+65 1638 the extinction was calculated from B-V photometry given by Racine (1968). If we place these three stars at the accepted distance of the cloud (1.15 kpc), their absolute magnitudes and corresponding luminosity classes are the following: –2.20 (B3 IV) for BD+65 1638, –2.14 (B4 III-IV) for BD+65 1637, and –1.27 mag (B7 III) for LkHα 234. In Table 3 these luminosity classes are given in parentheses. In the next section (see, e.g., equations 1 and 2 in Straižys et al. (2012) for details). The models have been computed by the Pisa group with the FRANEC stellar evolutionary code (see, e.g., Degl’Innocenti et al. (2008)), with input physics similar to those discussed in detail in Tognelli et al. (2011) and used to compute the PMS tracks currently available in the Pisa Stellar Models Database. The main differences with respect to those PMS tracks are the adoption of Asplund et al. (2005) solar heavy-element mixture instead of the Asplund et al. (2009) one, and the consequent slightly higher solar calibrated mixing length parameter value \( \alpha = 1.74 \). Another important difference is the adoption of a mild (i.e., \( \beta_\alpha = 0.2 \)) convective core overshooting in stellar models with \( M > 1.2 M_\odot \).

The positions of the six stars with respect to the evolution tracks allow to estimate their masses and ages, the results are given in Table 3. The ages of stars were read out from the evolution track tables at the nearest positions. Among the six stars, BD+65 1638 has the largest mass (about 7.2 \( M_\odot \)) and is the youngest (0.2 Myr). The star No. 96 has the smallest mass (2.4 \( M_\odot \)) and it is the oldest one (3.1 Myr).

It is worth to emphasize that the current generation of PMS models is still quite uncertain for ages younger than about 1 Myr (see e.g., Baraffe et al. (2002); Tognelli et al. (2011) and the discussion in the next section). Thus, one should be cautious in assigning very young ages to PMS stars.

The error bars for each star are shown. The errors of log \( L/L_\odot \) in Fig. 6 correspond to ±0.5 mag absolute errors of the accepted distance modulus of the cluster. The errors log \( T_{\text{eff}} \) correspond to an error of ± 1 decimal spectral subclass. Naturally, for the two Ae/Be stars the real errors should be larger due to lower accuracy of spectral classification, variability, presence of circumstellar disks and envelopes, possibility of anomalous extinction law in the circumstellar dust, etc. The mass and age of a star would be wrong if it were a binary. However, we have not found in the literature any indication on a possible duplicity of the six stars plotted in Fig. 6. The vertical error bars of the distance modulus give various mass errors for different stars – from zero to one solar mass.
7 THE INFRARED GROUP [BDS2003]31

About a decade ago Bica et al. (2003) have published a list of star groups which in the atlas of the infrared 2MASS survey look like open clusters. One of these ‘infrared groups’, [BDS2003]31, is located close to NGC 7129, with the center coordinates RA = 21°42′00″, DEC = +66°05′12″. In Fig. 1 this group of stars is surrounded by a 2′ × 2′ square.

It is evident that this group is not an infrared object since its 12 stars, seen in the K filter, are all observable in optical wavelengths. Most of these stars were measured in the Vilnius system (Table 1) and classified in two dimensions. We plotted for the group the A_v vs. d and the V_0 vs. (Y−V_0) diagrams. Both these plots do not confirm that these stars form a real cluster: their A_v are scattered within 0.3−1.8 mag, distances are within 0.4−5 kpc, and in the colour-magnitude diagram no sequence is seen. One of these stars, No. 27 in Table 1, in the 2MASS + WISE diagram K_s−[3.4] vs. [3.4]−[4.6] looks like YSO. Consequently, the object [BDS2003]31 is just an accidental asterism, i.e., a group of unrelated stars.

8 DISCUSSION

In the literature, there are a few estimates of the age of the NGC 7129 stars based on different methods. One of the methods is the estimation of the fraction of stars with the circumstellar disks (YSOs of class II) among the total cluster members. According to Gutermuth et al. (2004) this fraction is 54%, while Stelzer & Scholz (2009) find 33%. Comparing these fractions with the results for other young clusters, they estimate the age of NGC 7129 as 2−3 Myr and 3 Myr, respectively. Hernández et al. (2004), among other Herbig Ae/Be stars, have obtained new estimates of spectral classes for BD+65 1637 and LkHα 234. Combining these spectral classes with photometry from the literature, they found the positions of these stars in the log L/L_☉ vs. log T_eff diagram and, comparing with the PMS evolution tracks, estimated their masses and ages. The masses of these stars are 7.0 and 4.8 M_☉, and the ages are 0.29 and 0.83 Myr, respectively, in close agreement with our results, see Table 3. Kun et al. (2009), using their spectral classes and BVRI photometry in NGC 7129, have plotted in the log L/L_☉ vs. log T_eff diagram four NGC 7129 K–M stars of low masses. Three of them are found to be younger than 1 Myr. Increasing the distance from their 0.8 kpc to our 1.15 kpc leads to increase of the age but insignificantly. However, the observed magnitudes, colour indices and bolometric corrections of YSOs are usually affected by emission lines and infrared excesses, therefore the calculation of their positions in the theoretical HR plane can be inaccurate. This was one of the reasons why in the present paper we analysed only the massive stars close to the main sequence: four B-A stars with normal spectra and two Herbig Ae/Be stars.

According to the concept of Stahler (1983) (see also Stahler & Palla (2005) and Palla (2005)), all PMS tracks in the HR diagram should begin from a ‘birthline’ where the newborn stars first appear as visible objects. In the region of masses larger than 1 M_☉, this line runs approximately along the 0.5−1.0 Myr isochrones approaching the ZAMS. The birthline intersects ZAMS at about 7 M_☉ for the accretion rate 10⁻⁵ M_☉ yr⁻¹ and at about 15 M_☉ for the accretion rate 10⁻⁴ M_☉ yr⁻¹. Both these birthlines, BL1 and BL2, are plotted in Fig. 6 in blue. The positions of BD+65 1637 and BD+65 1638 are close to the birthline BL1 but are slightly above it. This difference can be related to the errors in their luminosities and the distance modulus of the cluster. However, as recently shown by Baraffe et al. (2012), the location of stars after the accretion phase is still an open issue, being strongly affected by several not yet well-constrained parameters (i.e., initial mass, accretion type, accretion energy, see also Hosokawa et al. (2011)). This might translate in a quite large luminosity and effective temperature spread in the HR diagram caused by the introduction of an early accretion phase, thus making the comparison between data and models even harder.

9 RESULTS AND CONCLUSIONS

1. Medium-band seven-colour photometry of 159 stars in the 13′ × 13′ area in the direction of the cluster and reflection nebula NGC 7129 in Cepheus is accomplished.

2. For 72 stars, using the interstellar reddening-free Q-parameters, photometric spectral and luminosity classes in the MK system are determined.

3. For these stars, supplemented with 83 stars from Paper I, the interstellar extinction vs. distance diagram in the 20′ × 20′ area centered on the cluster is plotted.

4. The distance to the interstellar dust cloud TGU H645 P2, which contains the embedded cluster, is found to be 1.15 ± 0.08 kpc. The extinction A_v in the cluster area exhibits the values between 0.6 and 2.8 mag. The extinction in the densest parts of the cloud, estimated from the J−H vs. H−K, diagram, has the values up to ~ 13 mag.

5. For determining the age of NGC 7129, six cluster members of spectral classes B3 to A1 were plotted in the log L/L_☉ vs. log T_eff diagram, together with the Pisa evolution tracks. Masses of the six stars are found between 7.2 and 2.4 M_☉ and the ages between 3.10 and 0.20 Myr.

6. We also conclude that the ‘infrared group’ [BDS2003]31, located about 6′ from the core of NGC 7129, is not a physical cluster.

ACKNOWLEDGEMENTS

The use of the Simbad, WEBDA, ADS and SkyView databases is acknowledged. We are grateful to Francesco Palla for consultations. The project is partly supported by the Research Council of Lithuania, grant No. MIP-061/2013.

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