The Pleiades flare stars in the Gaia era

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Abstract

We study the six-dimensional arrangement of flare stars in the Pleiades cluster region using the third release of the *Gaia*–mission (*Gaia* DR3) and we provide preliminary, a new, original view of the spatial configuration of the flare "star-members" of the cluster.

1. Introduction

Historically, star clusters have always been cornerstones for our knowledge of stellar evolution. The Pleiades is the best studied northern cluster and qualifies as a benchmark region (see, e.g. Lodieu et al., 2019). Numerous multi-wavelength surveys have been conducted in the region to study in depth the stellar and sub-stellar members. Pleiades members share a significant common proper motion compared to neighboring stars with $(\mu_\alpha \cos\delta,\, \mu_\delta) \sim (19.5,\, -45.5)$ mas/yr (Jones, 1981, van Leeuwen, 2009). This large mean motion, high galactic latitude ($b \sim 24°$), and low reddening along the line of sight of the cluster ($\mathrm{E}(B-V) = 0.03$ mag) makes it one of the best targets for comprehensive astrometric and photometric study. The cluster is also nearby, with the Hipparcos distance placing the Pleiades at 120.2 ± 1.9 pc (van Leeuwen, 2009) while other works suggest a mean distance of 134 pc with an uncertainty of 5 pc (Gatewood et al., 2000, Johnson & Mitchell, 1958, Pinfield et al., 2000, Southworth et al., 2005). The age of the cluster has also been debated in the literature, ranging from 70–130±20 Myr.

In 1954, Ambartsumian (1954), while analyzing the problem of the nature of continuous emission in the spectra of T Tauri type stars, called attention to the unusual observational fact that during the brief flares of UV Cet type stars, continuous emission also arises in their spectra. At the same time Haro (1954, 1956) suggested that the flare stars (FSs) in the vicinity of the Sun and the FSs in stellar associations belong to the same physical class of variables and might have a similar origin, i.e., that they represent different evolutionary stages of the common predecessors, namely, T Tauri or T Tauri–like stars.

Of decisive significance in the confirmation of this fundamentally new idea was the accidental discovery by Johnson & Mitchell (1958) of the first flare star in the Pleiades cluster. This discovery encouraged photographic observations which led to the detection of a several dozen FSs.

Ambartsumian (1969) developed a simple statistical method that makes it possible to estimate the total number of unknown FSs in any stellar system by the numbers of FSs to have flared up once and twice. By application of this method to the data of the Pleiades 68 FSs, known in that time, a conclusion was reached:

- All or almost all faint stars in the Pleiades cluster are FSs;
- The stage of flare activity is a regular stage in the evolution of red dwarf stars, through which all stars of this class must pass.

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These results were so important for the evolution of red dwarfs that they initiated a campaign of wide-field photographic observations at the many observatories which led to discovery and study FSs in the regions of different ages stellar clusters and associations. In particular, in the Pleiades cluster region were detected ~ 500 new FSs (HCG catalog, Haro et al., 1982, the catalog presents the data of 519 FSs). The list of FSs in the Pleiades region was completed by discovery of a new FSs after publication of the HCG catalog and contains the data of 547 FSs (hereafter the HCG+ catalog, Mirzoyan, 1993, 1495 flares during effective observational time of ~ 3200 hours) and the estimated total number of FSs is ~ 1000 (Akopian, 2021). The regular photographic observations with wide–angle telescopes of FSs of stellar groups stopped in the early 80th of the 20th century because of cardinal changes of types of detectors for astronomical observations.

Recently, in the literature reported studies of randomly flashing objects obtained with the Kepler orbital observatory. In particular, Ilin et al. (2021) for the Pleiades region inspected 741 light curves (provided by Kepler spacecraft 2009-2018 Koch et al. (2010) based on mission K2 "Second Light" Howell et al. (2014)) and detected 1583 flares of 487 stars, with the probability of membership $p > 0.8$ (Cantat-Gaudin et al., 2018, Olivares et al., 2018b, Rebull et al., 2016). Note that average flare frequency is much higher with Kepler observations in comparison to the above mentioned photographic ones (further analysis of the Kepler FSs data beyond the scope of this paper and will be published elsewhere).

Naturally, a question was raised: *Whether all FSs observed in the Pleiades region are members of the cluster, i.e. have common motion and are located in the same volume in the space?*

2. The Pleiades FSs *before* the Gaia mission

The first part of the question, i.e. common proper motion, was addressed using the catalog of members based on the extensive studies of astrometric, photometric, and spectroscopic observations of the Pleiades (e.g. Hambly et al., 1993, Haro et al., 1982, Hertzsprung, 1947, Jones, 1981, Schilbach et al., 1995, Stauffer, 1982, 1984, Stauffer et al., 1991, among others).

Naturally, apart from the Pleiades FSs members, several non–member FSs of the cluster have been found. Some of the latter belong to the Hyades, others to the solar vicinity (i.e., foreground stars), probably others to some yet unidentified stellar system, or simply to the general Galactic field (background stars).

The question is: *What is the percentage of non–members among observed FSs in the Pleiades cluster region?*

For computing cluster membership, above mentioned various authors (e.g., Hambly et al., 1993, Schilbach et al., 1995, Stauffer et al., 1991), used a method (e.g., Sanders, 1971, Vasilevskis et al., 1958) which proposes to fit the sum of two bi–dimensional Gaussians or a combination of a Gaussian and a linear model to the proper motion distribution. For selecting reliable members of the cluster, a photometric criterion also was used. This approach assumes a common nature of motions of all members and did not yield realistic results (e.g., Schilbach et al., 1995). It excludes the possibility of the existence of different moving groups within the same stellar system arising from non–coeval star formation, or does not take into account the orbital motion of double and chaotic motion of multiple stars, which distorts the general picture of the established distribution of motions.

The first indication that flare activity could be possibly used as a reliable criterion for determining the membership of stars in stellar systems was obtained from the discussion of the distribution of FSs in the Pleiades cluster region. Namely, the space distribution of FSs in the Pleiades cluster showed (e.g., Chavushian, 1979, Chavushian et al., 1999, 2004, Hambaryan, 1998, Mirzoyan, 1976, 1983, Mirzoyan et al., 1993) that the concentration of FSs around the center of the Pleiades cluster is the same, i.e. the surface density of FSs decreases upon distance from the center of cluster, irrespective their proper motion or membership probability.

Nevertheless, these studies showed that significant number of FSs in the Pleiades region can be considered as *non–members* (52% and 35%, Hambly et al., 1993, Jones, 1981, accordingly).

An alternative estimate of the expected number of classical FSs (UV Cet type) to be detected by photographic multi-exposure method of observations of the Pleiades cluster region and belonging to the general Galactic star field, under assumption that UV Cet type stars distributed uniformly, is ~ 170, (i.e., not exceeding 20% Hambaryan, 1998, Mirzoyan et al., 1988).

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3. The Pleiades FSs with *Gaia* DR3

Given the unprecedent precise astrometric and kinematic parameters of stars provided by *Gaia* DR3 release a numerous surveys of distinct sizes and depths have looked at the Pleiades (see, e.g., Heyl et al., 2022, Hunt & Reffert, 2023, Lodieu et al., 2019, Olivares et al., 2018a,b, Qin et al., 2023, see their references). Most of them provided also member list of the Pleiades (1100-1300 member stars) and characteristic parameters, such as core and tidal radii (r_{core} = 2.5-3.5pc and r_{tidal} = 10-18pc), of the cluster.

We have identified FSs from HCG+ catalog in the Pleiades region with *Gaia* DR3 sources and verified it by using identification charts. In addition we identified them also with most recent Pleiades member star list (Qin et al., 2023) also based on the *Gaia* DR3 data. In Fig. 1 are presented results of this identification and some analysis of them depending on the observed distances of the FSs in the Pleiades cluster region. It also suggests that $\sim 30\%$ of the observed FSs can be considered as *non–members* of the Pleiades cluster from the point of view of the common proper motion and allocation in the same volume in the space.

A catalog and identification charts of the Pleiades flare stars (519 FSs),
Haro, G.; Chavira, E.; Gonzalez, G. 1982, (completed, i.e. HCG+)

HCG+ catalogue of the Pleiades Flare Stars: → 547

With Gaia DR3 Ids

Number of the Pleiades FSs with 2 parameters solution → 503
Number of the Pleiades FSs with 5 parameters solution → 492
Number of the Pleiades FSs with 5 parameters solution +
Radial velocities → 211 (320 with Simbad database)

$$\frac{Plx}{e\_Plx} \geq 5 \;\&\; RUWE < 1.4 \qquad R_{tidal} = 11.3\,pc;\quad d_{Pleiades} = 135.15pc$$

RUWE -> a renormalized unit weight error

$$N_{FS} = \begin{cases} 15, & d \leq 100pc \\ 326, & 100 < d < 170 \\ 151, & d \geq 170\,pc \end{cases}$$

$$N_{FS} = \begin{cases} 15, & d \leq 100pc \\ 336, & 100 < d < 200 \\ 141, & d \geq 170\,pc \end{cases}$$

Percentage of „non-members“ ≈ 30%

Figure 1. Identification of the Pleiades FSs (HCG+) with *Gaia* DR3.

Moreover, the distribution of parallaxes and proper motions also show double–peaked shape of all FSs stars observed in the Pleiades cluster region and having *Gaia* DR3 ID numbers (see, Fig. 2).

In contrary, distribution of radial velocities is uni-modal (Fig.2) and angular distribution of the FSs around the center of the Pleiades cluster does not show any significant asymmetry (Fig.3).

These results can be interpreted with a number of statements:

- Two groups of flare stars with different flare activity levels;
- Coeval/Non-coeval star formation;
- Another distant star cluster in the background of the Pleiades;

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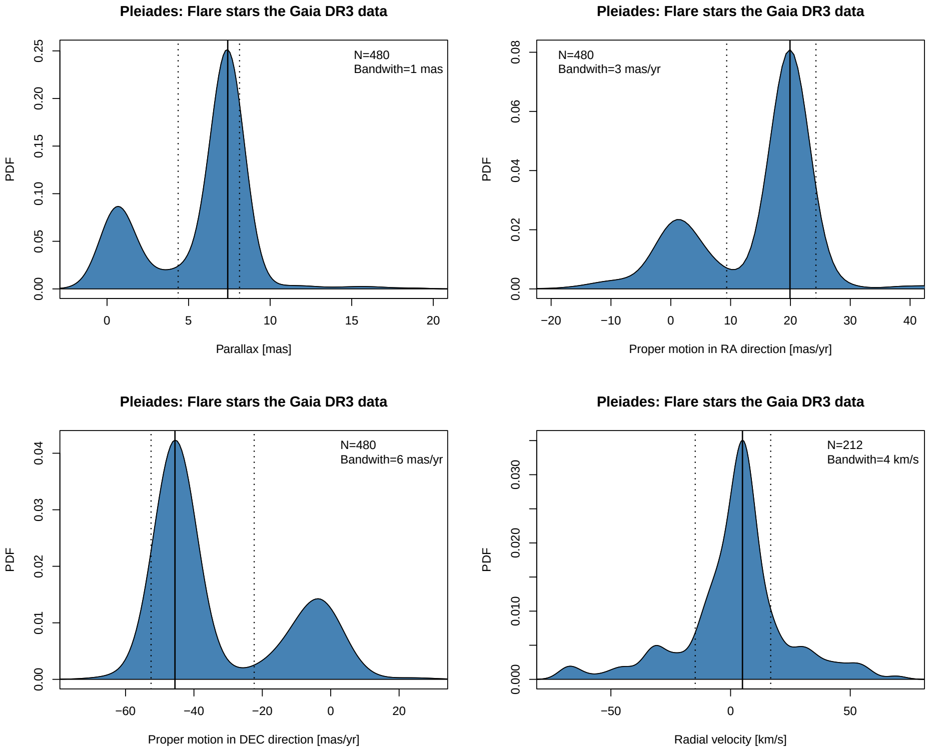

Figure 2. Distribution of the Pleiades FSs astrometric and kinematic parameters based on the data of *Gaia* DR3

- Owing to the dynamical evolution of the Pleiades open cluster some number of stars have already escaped it, and currently are in the same evolutionary stage, i.e. showing similar flaring activity as member stars of the same mass.

The last possibility was not considered in the previous studies of FSs observed in the Pleiades cluster region. Most recently, Heyl et al. (2022) reconstructed the Pleiades with *Gaia* EDR3 by selecting all objects within 100 pc of the Sun and all sources within 200 pc of the Sun that lie within 45° of the Pleiades on the sky and divided into two groups, i.e. member stars and escapees (i.e., evaporated stars owing to the dynamical evolution of a stellar cluster). Namely, to find the center-of-mass motion and position for the Pleiades, the proper, motions of all stars within one degree on the sky from the center of the cluster was determined and by using those stars within the sample that have radial velocities measured with *Gaia* DR2, the reconstruction for the others was performed, and the mean velocity of the stars of the Pleiades cluster relative to the Sun was estimated: $v_{cluster} = (-7.1 \pm 0.4; -28.3 \pm 0.1; -144 \pm 0.2)\ km/s$. Using all the stars within the sample, the mean displacement of the cluster relative to the Sun was calculated: $d_{cluster} = (-120.99 \pm 0.20; 28.96 \pm 0.06; -54.23 \pm 0.10)\ pc$. To find the escapees, the evaporated velocity was computed assuming that the $v_{evaporated} \approx \sqrt{2} * v_{\sigma}$. $v_{\sigma} \approx 2.4\ km * s^{-1}$, so $v_{evaporated} \approx 3.4\ km * s^{-1}$. We have revisited these lists and completed with the data (mainly radial velocities) of *Gaia* DR3 and *Simbad astronomical database*. In the Fig. 4 are shown distribution of the member and evaporated stars around of the center–of–mass of the Pleiades cluster and in the inner panels of the figures (see, Fig.4) are given kinematic characteristics of them using 3D positions and velocities. Obviously, evaporated stars are distributed over much greater distances from the center–of–mass, showing also greater velocities in comparison to the member ones.

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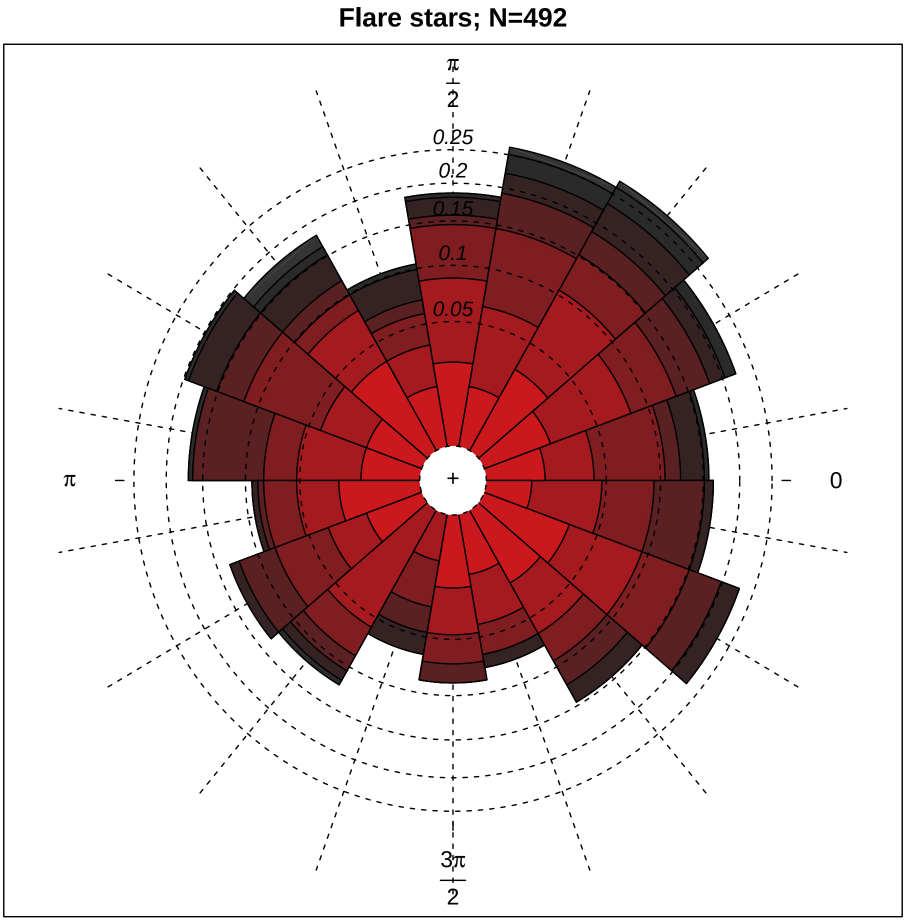

Figure 3. A succinct view of the angular distances and directions of 492 FSs relative to the center of the Pleiades cluster based on the data of *Gaia* DR3.

Despite to the slightly different occupied regions on the sky, we have compared and cross-matched lists of Pleiades member stars presented in the three catalogs (HCG+, Ilin et al. (2021) and Heyl et al. (2022)). It is noticeable that Heyle's 24 escapee stars are included in Ilin's catalogue of flare stars. Also 289 Heyl escape stars and 492 HCG+ member stars have 8 overlaps.

Next, we identified FSs (HCG+ catalog) observed in the Pleiades cluster region with Heyl et al. (2022) lists and performed trace-back motion analysis (see, e.g. Hambaryan et al., 2022, Neuhäuser et al., 2020) of FSs–escapees. It showed, that out of 109 non–member FSs 69 (63%), most probably, were within the tidal radius (11.3 pc) of the Pleiades cluster in the past $\sim$ 3-8 Myr ago.

4. Concluding remarks

Despite significant number of FSs observed in the Pleiades cluster region can be considered as "non–members", i.e. do not show common proper motion and not located in the same volume in the space, nevertheless, they must be considered as members of the Pleiades cluster from the evolutionary point of view, i.e. they are in the same, flare activity stage of red dwarf stars.

Thus, depending on the astrophysical problem:

1) To study present day mass function or distribution FSs around to the center of the cluster:
   - classical membership is preferable.
2) For statistical estimators of flare frequencies:
   - flybys and escapees must be taken into account.

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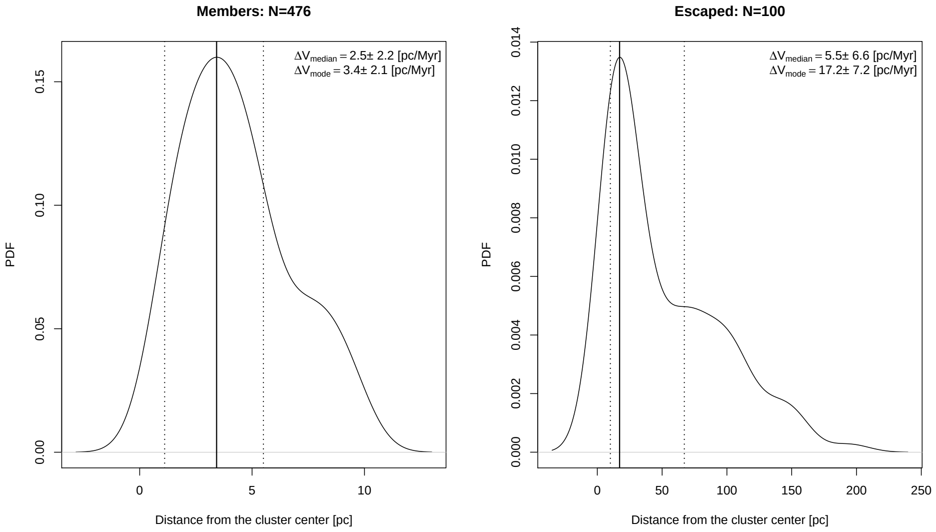

Figure 4. Distribution of member and escaped stars of the Pleiades cluster using 3D positions and velocities based on the *Gaia* DR3 data.

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References

Akopian A. A., 2021, Communications of the Byurakan Astrophysical Observatory, 68, 150

Ambartsumian V. A., 1954, Communications of the Byurakan Astrophysical Observatory, 13, 3

Ambartsumian V., 1969, Publ. House Acad. Sci. Armenian SSR. Yerevan, p. 283

Bouy H., et al., 2015, Astron. Astrophys. , 577, A148

Cantat-Gaudin T., et al., 2018, Astron. Astrophys. , 618, A93

Chavushian H., 1979, PhD thesis, Byurakan Astrophysical Observatory, p. 283

Chavushian H. S., Oskanian A. V., Broutian G. H., 1999, Astrophysics, 42, 404

Chavushian H. S., Pikichian H. V., Oskanian A. V., Broutian G. H., 2004, Astrophysics, 47, 313

Feigelson E. D., Babu G. J., 2012, Modern Statistical Methods for Astronomy. Cambridge University Press

Gaia Collaboration et al., 2018, Astron. Astrophys. , 616, A10

Gatewood G., de Jonge J. K., Han I., 2000, Astrophys. J. , 533, 938

Hambaryan V. V., 1998, in Donahue R. A., Bookbinder J. A., eds, Astronomical Society of the Pacific Conference Series Vol. 154, Cool Stars, Stellar Systems, and the Sun. p. 1492

Hambaryan V., et al., 2022, Mon. Not. R. Astron. Soc. , 511, 4123

Hambly N. C., Hawkins M. R. S., Jameson R. F., 1993, Astron. and Astrophys. Suppl. Ser. , 100, 607

Haro G., 1954, Boletin de los Observatorios Tonantzintla y Tacubaya, 2, 11

Haro G., 1956, Boletin de los Observatorios Tonantzintla y Tacubaya, 2, 8

Haro G., Chavira E., Gonzalez G., 1982, Boletin del Instituto de Tonantzintla, 3, 3

Hertzsprung E., 1947, Annalen van de Sterrewacht te Leiden, 19, A1

Heyl J., Caiazzo I., Richer H. B., 2022, Astrophys. J. , 926, 132

Howell S. B., et al., 2014, Publications of the Astronomical Society of the Pacific, 126, 398

Hunt E. L., Reffert S., 2023, Astron. Astrophys. , 673, A114

Ilin E., Schmidt S. J., Poppenhäger K., Davenport J. R. A., Kristiansen M. H., Omohundro M., 2021, Astron. Astrophys. , 645, A42

doi: https://doi.org/10.52526/25792776-23.70.2-242

Johnson H. L., Mitchell R. I., 1958, Astrophys. J. , 128, 31

Jones B. F., 1981, Astron. J. , 86, 290

Koch D. G., et al., 2010, The Astrophysical Journal Letters, 713, L79

Lodieu N., Pérez-Garrido A., Smart R. L., Silvotti R., 2019, Astron. Astrophys. , 628, A66

Mirzoyan L. V., 1976, in Kharadze E. K., ed., Stars and Galaxies from Observational Points of View. pp 121–127

Mirzoyan A. L., 1983, Astrofizika, 19, 588

Mirzoyan L. V., 1993, Astrofizika, 36, 277

Mirzoyan L. V., Ambaryan V. V., Garibdzhanyan A. T., Mirzoyan A. L., 1988, Astrofizika, 29, 531

Mirzoyan L. V., Hambarian V. V., Mirzoyan A. L., 1993, Astrofizika, 36, 395

Neuhäuser R., Gießler F., Hambaryan V. V., 2020, Mon. Not. R. Astron. Soc. , 498, 899

Olivares J., et al., 2018a, Astron. Astrophys. , 612, A70

Olivares J., et al., 2018b, Astron. Astrophys. , 617, A15

Pinfield D. J., Hodgkin S. T., Jameson R. F., Cossburn M. R., Hambly N. C., Devereux N., 2000, Mon. Not. R. Astron. Soc. , 313, 347

Qin S., Zhong J., Tang T., Chen L., 2023, Astrophys. J. Suppl. Ser. , 265, 12

Rebull L. M., et al., 2016, The Astronomical Journal, 152, 113

Sanders W. L., 1971, Astron. Astrophys. , 14, 226

Sarro L. M., et al., 2014, Astron. Astrophys. , 563, A45

Schilbach E., Robichon N., Souchay J., Guibert J., 1995, Astron. Astrophys. , 299, 696

Southworth J., Maxted P. F. L., Smalley B., 2005, Astron. Astrophys. , 429, 645

Stauffer J. R., 1982, Astron. J. , 87, 1507

Stauffer J. R., 1984, Astrophys. J. , 280, 189

Stauffer J., Klemola A., Prosser C., Probst R., 1991, Astron. J. , 101, 980

Stauffer J. R., Schultz G., Kirkpatrick J. D., 1998, Astrophys. J. Lett. , 499, L199

Vasilevskis S., Klemola A., Preston G., 1958, Astron. J. , 63, 387

van Leeuwen F., 2009, Astron. Astrophys. , 497, 209

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