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FLARE ACTIVITY OF STARS AS A CLUSTER MEMBERSHIP CRITERION

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The flare activity is examined as a reliable criterion for cluster membership of stars. This conclusion follows directly from the observational fact that all known flare stars in region of the Pleiades cluster are concentrated around the centre of the cluster irrespective of the membership probabilities calculated on the base of their proper motions. This means that in this case the flare activity is more effective membership criterion than proper motion. It is in complete agreement with the results of the statistical study of the space distribution of flare stars in the Galaxy. It shows that almost all flare stars of the comparatively high luminosities are members of star clusters and associations and only flare stars of the lowest luminosities (of the UV Ceti type of solar vicinity) consist of the characteristic population of general galactic star field. New cluster membership probabilities of 408 Pleiades flare stars based on the proper motions and the data concerning the existence of strong emission at H_α and H and K of Ca II lines in spectra of flare stars are discussed in favour of the flare activity as a cluster membership criterion.

1. *Introduction.* Usually the proper motion of a star is accepted as satisfactory criterion of its membership in the nearby cluster. Thus in the extensive study of star proper motions in the central part of the Pleiades region Hertzsprung et al [1] have used the closeness of the proper motions of stars to that of the brightest member of the cluster - Alcione as the membership criterion.

Later on a method has been worked out to calculate membership probabilities of the stars in the nearby stellar systems on the base of their proper motions (see, for example [2]).

The membership probabilities of the Pleiades flare stars determined by this method by Jones [3] were used to estimate the portion of the general galactic field flare stars among the flare stars detected in this region. It turned out that this portion is unexpectedly large.

However the study of this problem showed that for flare stars of the Pleiades region the criterion of proper motions is apparently incorrect. As it has been revealed by one of the authors [4] all flare stars in the Pleiades region are concentrated around the centre of cluster irrespective of their proper motions.

This unusual result has been confirmed by Chavushian [5] and later on by one of the authors [6] on the base of more richer observational data concerning proper motions of the Pleiades flare stars.

In agreement with this result the statistical study of the space distribution of flare stars in the solar vicinity has shown [7,8], that all flare stars in the Galaxy having comparatively high luminosity are members of star clusters and associations.

Proceeding from this significant observational fact it has been suggested that the flare activity is more effective criterion of the cluster membership than proper motion, at least in the case of the Pleiades cluster [9].

Recent papers devoted to the search of faint members of the Pleiades cluster by Stauffer et al [10] and Prosser et al [11] as well as some observational data on flare stars contain new additional testimonies in favour of this conclusion.

In the present paper these new testimonies are discussed in favour of our former conclusion that the flare activity is a reliable criterion for cluster membership.

2. *The distribution of flare stars around the centre of the Pleiades cluster.* The first indication on the possibility of using the flare activity as a reliable criterion for the membership of stars in the nearby stellar system (cluster or association) has been obtained from the discussion of the distribution of flare stars in the Pleiades cluster region.

Namely, the space distribution of flare stars in the Pleiades cluster showed [4-6] their concentration around the centre (Alcione) of this system irrespective of the cluster membership probabilities calculated on the base of proper motions of stars.

This conclusion, showing that proper motion of a star, at least in the case of the Pleiades cluster flare stars, is not a satisfactory criterion of the cluster membership can be examined using the new membership probabilities of 408 flare stars from the Pleiades flare star Catalogue by Haro, Chavira and Gonzalez [12] (hereafter referred the HCG

Catalogue), recently determined by Stauffer et al [10] on the base of proper motions.

The surface distribution of all Pleiades flare stars with the known membership probabilities [10] around the centre of the Pleiades cluster (Alcione)* was determined by the two following ways.

1). All flare stars were divided into two groups by their membership probabilities. The flare stars for which the membership probability p is equal or larger 0.5 were accepted as "members" of the cluster, and those flare stars for which p is smaller than 0.5 were accepted as "non-members".

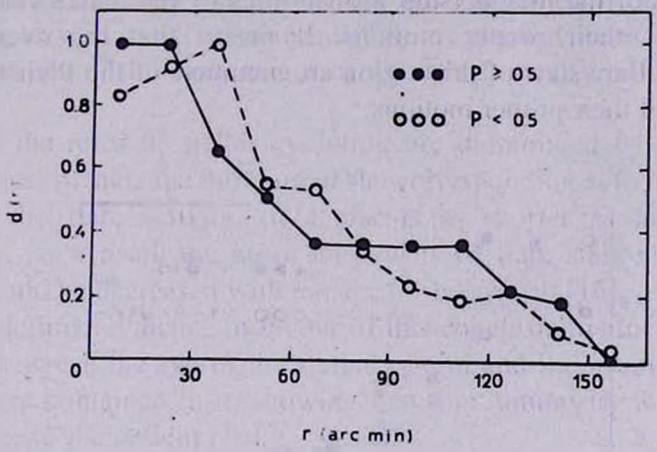

Fig. 1. The surface distribution of flare stars around the centre of the Pleiades cluster: 1) "members" (membership probability $p \geq 0.5$) and 2) "non-members" ($p < 0.5$), where p is cluster membership probability determined by Stauffer et al [10], on the base of star proper motions.

The surface distribution of these two groups of flare stars around Alcione, are presented in Fig. 1. It shows that the surface density of stars - "non-members" decreases with the increase of the distance from the Pleiades cluster centre almost similar to the density of stars-"members" of the cluster.

*As our determination has shown the mass centre of Pleiades cluster on the base of 291 members according to Hertzsprung et al [1] does not differ significantly from the position of Alcione (the difference is equal to about 7 arc min.).

2). The surface distribution of flare stars around the centre of the Pleiades cluster were determined also, as in the paper [6], taking as weights of the stellar density the magnitudes p and 1-p. The corresponding surface distribution of flare stars around the cluster centre are presented in Fig. 2.

Fig. 1 and 2 show that in both considered cases the decrease of the flare stars density with the increase of the distance from the cluster centre is observed.

Thus, the consideration of the surface distributions for 408 Pleiades flare stars (Table 3 by Stauffer et al [10]) confirms our conclusion that all of them are concentrated around the centre of the Pleiades cluster irrespective of the membership probabilities of flare stars calculated on the base of their proper motions. It means that the overwhelming majority of flare stars of this region are members of the Pleiades cluster, regardless of their proper motions.

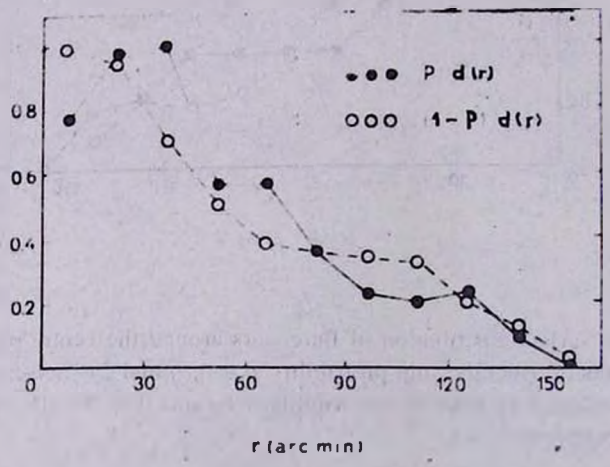

Fig. 2. The surface distribution of flare stars around the centre of the Pleiades cluster: 1) $p\,d(r)$ and 2) $(1-p)\,d(r)$, where p is cluster membership probability obtained by Stauffer et al [10], on the base of star proper motion.

3. *The distribution of flare stars in the Galaxy.* The study of the space distribution of the UV Ceti type flare stars of the solar vicinity and the comparison of the number of flare stars expected to be discovered from this distribution with the number of flare stars detected

by the photographic multi-exposure observations of the Pleiades region using wide-angle telescopes allowed to conclude that almost all flare stars of comparatively high luminosity in the Galaxy are members of star systems (clusters and associations) [7,8]. And only the flare stars of lowest luminosity (e.g. UV Ceti type flare stars of solar vicinity) consist of the characteristic population of general star field of the Galaxy, preserving their flare activity after the disintegration of the "maternal" systems. The percentage of them among the flare stars discovered in the regions of star clusters and associations is estimated to be of the order of 10% [8].

The consideration of this problem has shown that such space distribution of flare stars in the Galaxy is conditioned by the fact that flare stars, as well as all stars in general, are formed in stellar systems and present one of the early stages of red dwarf stars (see, for example, [13-15]).

Since the rates of stellar evolution are determined by the masses (luminosities) of stars the duration of the corresponding activity phase, in particular the flare activity, of a star is as shorter as higher is its luminosity. As a result the mean luminosity of flare stars in the stellar system should be decreased with the age of the system [16].

As a definite evidence in favour of this conclusion is the correlation observed between the age of the stellar system and the mean luminosity of flare stars contained in it, showing that this luminosity is decreasing with the age of the system [16].

The photographic multi-exposure observations of flare stars in various regions of the sky support this important conclusion. They showed that during these observations one flare was detected in some hours-in regions of star clusters and associations, and more than one hundred hours-in the general galactic star field. For example, during photographic multi-exposure observations of the Pleiades region with the 40" Schmidt telescope of the Byurakan Astrophysical Observatory each flare was detected in 1-2 hours, on the average, whereas the observations of the general galactic star field with 40" and 21" Schmidt telescopes during 181 hours brought to the detection of one single flare. It means that the flare stars of comparatively high luminosity actually are absent in the general galactic star field [5,14].

From the point of view of this regularity it is significant to clear up the discrepancy between the membership probabilities of flare stars and

their distribution in the Pleiades region. It is not probable to think that it is conditioned by the fact that the cluster proper motion is rather small since it lies in a direction near the solar antiapex of galactic rotation [10].

For clearing up this question it is important to see the situation in other subsystems of flare stars. Unfortunately there are not enough determinations of proper motions of flare stars in other regions.

Nevertheless, it seems that the existing scanty data on the proper motions of flare stars in the Orion association don't contradict the conclusion that almost all flare stars of comparatively high luminosit are members of star clusters and associations. Indeed, the cluster membership probabilities of a few flare stars near the Orion nebula determined by Jones and Walker [17] based on their proper motions confirms this conclusion.

Table 1

MEMBERSHIP PROBABILITIES OF THE KNOWN FLARE STARS NEAR THE ORION NEBULA ACCORDING TO JONES AND WALKER [17]

Number			I	MP
[18]	[19]	[20]	[17]	[17]
181	1477	V976 Ori	12.7	0.97
213	1588	-	13.4	0.00
231	-	V551 Ori	13.4	0.99
239	1667	KO Ori	12.0	0.97
250	-	V408 Ori	14.4	0.99
254	1805	V557 Ori	13.6	0.99
255	1827	V488 Ori	11.9	0.99
267	1988	-	12.9	0.88
285	2112	V803 Ori	13.1	0.99
294	2172	V569 Ori	12.4	0.01
295	2185	OR Ori	11.8	0.83
296	2184	V570 Ori	13.5	0.99
300	-	V808 Ori	14.5	0.99
303	2207	-	13.3	0.98
304	2209	V427 Ori	13.4	0.99
314	2235	V947 Ori	13.0	0.92
315	2246	OT Ori	13.7	0.88
318	2245	V379 Ori	13.5	0.78
323	2270	OX Ori	13.6	0.99
329	2295	V365 Ori	13.7	0.00
331	2305	V578 Ori	12.2	0.95

Table 1 contains the data concerning the Orion flare stars: number of stars from the Catalogue of the Orion flare stars by Natsvlishvili [18], Parenago's [19] list and from the General Catalogue of Variable Stars - GCVS [20], respectively, I - magnitude and MP - membership probability determined by Jones and Walker [17].

As of 21 flare stars in Orion (about 85%) are according to Table 1 members of nearby cluster. Only 3 flare stars having cluster membership probabilities close to 0 can be non-members of the cluster.

Thus, Table 1 can be considered as an additional evidence in favour of the conclusion that the majority of flare stars of comparatively high luminosities are members of star clusters and associations.

4. *Correlation between the membership probabilities and luminosity of the Pleiades flare stars.* As it has been shown in section 2 the new membership probabilities of 408 Pleiades flare stars determined by Stauffer et al [10] fully confirmed their concentration around the centre of the cluster irrespective of these membership probabilities.

On the other hand it can be shown that these membership probabilities are in general agreement with the statement that almost all flare stars of comparatively high luminosities are members of stellar systems populating the Galaxy.

Table 2

THE DISTRIBUTION OF THE MEMBERSHIP PROBABILITIES FOR THE PLEIADES FLARE STARS FROM THE HCG CATALOGUE [12] BY THE MAGNITUDE ACCORDING TO STAUFFER ET AL [10]

P	Number of stars
0.0 - 0.2	193
0.2 - 0.4	14
0.4 - 0.5	7
0.5 - 0.6	13
0.6 - 0.8	56
0.8 - 1.0	125
Total	408

The distribution of the membership probabilities of the Pleiades flare stars by the visual magnitude according to Stauffer et al [10] is

presented in Table 2. It shows that approximately half of the flare stars detected in the Pleiades region are "members" of the cluster ($p \geq 0.5$).

However, as the IICG Catalogue shows [12], the portion of probable "members" of the Pleiades cluster with the membership probabilities $p \geq 0.5$ among all known flare stars of this region is quite different for stars of various magnitudes. It increases to flare stars of higher luminosities.

Indeed, Table 3 containing the data for two groups of flare stars of different luminosities shows that the portion of probable "members" of the Pleiades cluster ($p \geq 0.5$) among the known flare stars of this region for flare stars of visual magnitudes 12-16.5 is two times larger than for flare stars fainter than 16.5 magnitude.

Table 3

CORRELATION BETWEEN THE MEMBERSHIP PROBABILITIES CALCULATED BY STAUFFER ET AL [10] AND LUMINOSITY OF THE PLEIADES FLARE STARS

V	N_t	$N_{p\geq0.5}$	$N_{p\geq0.5}/N_t$
12.0-16.5	268	157	0.59
16.5-19.0	139	41	0.30

Note. N_t is total number of flare stars and $N_{p\geq0.5}$ number of stars with $p \geq 0.5$.

It means that among the flare stars of comparatively higher luminosity the probable "members" of the Pleiades cluster meet more frequently in comparison with flare stars of lower luminosity. The detailed consideration of this problem confirms this conclusion. It turned out that the portion of the probable "members" of the Pleiades cluster among all known flare stars is decreasing regularly from about 90% for flare stars of 12-13 magnitudes to about 20% for stars of 18-19 magnitudes.

It should be added that the increasing tendency of flare stars to be probable "members" of a stellar system (star cluster or association) with the luminosity has, as it was shown, of the evolutionary significance.

This remarkable fact can be considered in favour of our former conclusion that almost all flare stars of comparatively high luminosity are members of star clusters and associations.

5. Flare activity as a criterion for cluster membership. Thus, the flare stars of comparatively high luminosity are usually members of stellar systems (clusters and associations) and only the flare stars of lowest luminosities occur in general galactic star field [7,8,15,21].

Notable evidence in favour of this regularity is the inverse correlation observed between the age of stellar system and the mean luminosity of flare stars contained in it [16].

It was revealed that this significant regularity of the space distribution of flare stars in the Galaxy is a direct consequence of the evolutionary status of flare stars and their formation in stellar systems [13-15].

This significant regularity allows to suggest that the flare activity of comparatively high luminosity stars can be considered as a reliable criterion of the membership to the nearby stellar system. The photographic observations of flare stars in star clusters and associations confirming this conclusion show that in some cases, for example in the Pleiades cluster, the flare activity is more powerful criterion of the cluster membership, on the average, than the proper motion [9].

However; the detection of flare activity, especially for stars with small flare frequencies, is very difficult. For example, at present the total duration of the photographic multi-exposure observations of the Pleiades cluster region with wide-angle telescopes for the detection of flare stars exceeds 3000 hours and only about a half of all flare stars in the cluster were detected [22]. The matter is that the majority of the Pleiades flare stars has very small flare frequencies [23].

Therefore, for practical purposes it is necessary to use an other criterion substituting the flare activity which can be determined easier. The presence of strong emission lines in spectra of flare stars is such a criterion.

6. The presence of strong emission lines in spectrum of a red dwarf star is a manifestation of its flare activity. The observations have shown (see, for example [24,25]) that almost all spectroscopic studied flare stars of the Pleiades region have rather intense emission lines of hydrogen and ionized calcium in their spectra. It means that the existence of strong emission lines in the spectra of stars is a manifestation of their flare activity.

New observations obtained by Prosser et al [11] confirm this conclusion. It turned out that of 57 red dwarf stars selected on the basis

of proper motion as members of the Pleiades cluster, and having pMK > M0.0*, 51 had shown well-detected H_α - emission [Equivalent width-EW(H_α) > 1Å].

This result allowed Prosser et al [11] to conclude that "it seems fairly certain that in spectroscopic survey of the Pleiades field at a resolution of ~ 5Å one would recover all but 10% - 20% of the Pleiades members which have spectral types between M0 and M5".

Therefore, the result obtained by Prosser at al [11] can be considered as an evidence that for flare stars in the Pleiades region the H_α-emission is an effective criterion of the flare activity and therefore the cluster membership.

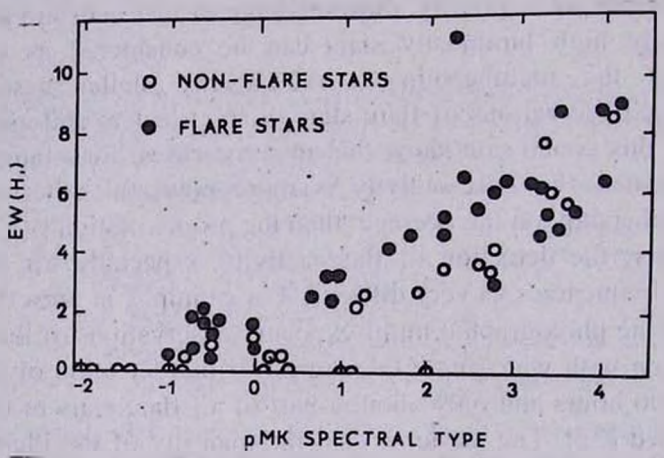

Fig. 3. Equivalent widths (EW) of emission line H_α for flare and non-flare stars of the Pleiades cluster according to Prosser et al [11].

Fig. 3 adopted from Prosser at al [11] paper shows that there is substantial difference in H_α-emission strength at a given spectral type between flare and non-flare "members" of the Pleiades. The equivalent width (EW) of the H_α-emission in the spectra of flare stars is larger than that in the spectra of non-flare stars. A few deviations from this regularity can be conditioned by two following circumstances.

"Non-flare" stars with strong H_α-emission can be really flare stars not yet detected. The matter is that, as Ambartsumian [26] has shown, all

* pMK - equivalent pseudo - MK types derived on the base of the spectral indices due to largely to TiO.

or almost all low luminosity stars in the Pleiades cluster must be flare stars.

Flare stars with faint H_α-emission can be non-members of cluster with low luminosity, i.e. flare stars of galactic star field. It is likely that emission spectrum in these flare stars is comparatively fainter as in the spectra of the UV Ceti stars. As it was mentioned the portion of the galactic field flare stars among all flare stars in the regions of the star clusters and associations is of the order of 10% [8].

Taking into account these circumstances Fig. 3 can be considered in favour of the conclusion that the existence of the strong H_α - emission in the spectrum of a star is manifestation of flare activity and therefore is a criterion of its membership in the nearby cluster.

This conclusion is in complete agreement with the early result obtained by Kraft and Greenstein [27]. In the spectral study of Hyades and Pleiades red dwarf stars it has been shown, that "the existence of strong emission H and K (of Ca II - *authors*) is a powerful criterion for cluster membership, if applied to clusters as young as Pleiades".

Thus, all above-mentioned results seem to be telling testimonies in favour of the idea that the existence of strong emission lines in the spectra of red dwarf stars i.e. the flare activity is indeed a reliable criterion for the cluster membership.

7. *Discussion.* In present paper we have discussed some existing observational data in the light of the supposition that the flare activity is a powerful criterion for cluster membership.

As it was shown earlier [4-8] the distribution of the flare stars around the centre of the Pleiades cluster shows their concentration irrespective of the membership probabilities, i.e. the concentration of the flare stars is almost the same for all flare stars; "members" and "non-members". This result is confirmed by using the new cluster membership probabilities of 408 Pleiades flare stars determined recently by Stauffer et al [10] on the base of proper motions (Fig. 1 and 2).

It means that flare stars - "non-members" of the Pleiades are connected with the cluster as well as flare stars - "members" of it, i.e. they are in fact also the members of this system. Consequently, in the case of the Pleiades region flare stars the flare activity is more effective criterion of the cluster membership than the membership probability calculated on the base of proper motion.

This result is a consequence of the general idea that almost all flare stars possessing comparatively high luminosity are members of clusters and associations. This idea obtained from the statistical study of the space distribution of flare stars in the Galaxy and conditioned by the evolutionary status of flare stars is supported by photographic observations of these red dwarf stars in various regions of the sky.

New observational data confirm this significant idea.

The cluster membership probabilities of flare stars in the region near the Orion nebulae, determined by Jones and Walker [17] testify that 85% of them are members of the Orion association (Table 1). The observed correlation between the cluster membership probabilities and luminosity of flare stars in the Pleiades region show (see, for example, Table 3) that these probabilities are increasing with the luminosity. It means that to be members of stellar systems for flare stars of comparatively higher luminosity is really a characteristic feature.

Finally the presence of strong emission lines in spectrum of red dwarf stars is examined as a manifestation of the flare activity.

The existence of strong emission lines H and K of Ca II, and H_α in spectra of flare stars in the Pleiades discussed by Kraft and Greenstein [27], Prosser et al [11] and in general for all flare stars, have been considered as striking illustration of their flare activity.

On the base of these results one can conclude that the flare activity of comparatively high luminosity flare stars, is a powerful criterion for their cluster membership. It is a direct consequence of the evolutionary status of flare stars, presenting one of the early stages of the red dwarf star evolution (see, for example, [28]).

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ВСПЫШЕЧНАЯ АКТИВНОСТЬ ЗВЕЗД КАК КРИТЕРИЙ ПРИНАДЛЕЖНОСТИ СКОПЛЕНИЮ

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Вспышечная активность рассматривается как надежный критерий принадлежности звезд к близлежащему скоплению. Этот вывод прямо следует из наблюдательного факта свидетельствующего, что все известные вспыхивающие звезды области скопления Плеяды сконцентрируются вокруг центра скопления независимо от их

вероятностей членства, вычисленных на основе собственных движений звезд. Это означает, что в этом случае вспышечная активность является более эффективным критерием принадлежности скоплению, чем собственное движение. Этот критерий находится в полном согласии с результатами статистического исследования пространственного распределения вспыхивающих звезд в Галактике. Они показывают, что почти все вспыхивающие звезды сравнительно высоких светимостей являются членами звездных скоплений и ассоциаций. Только вспыхивающие звезды наиболее низких светимостей (типа UV Kita окрестностей Солнца) составляют характерное население общего галактического звездного поля. Новые вероятности членства вспыхивающих звезд области скопления Плеяд, основанные на собственных движениях 408 звезд и данные относящиеся к существованию сильных эмиссионных линий H_α и H и K Ca II в спектрах вспыхивающих звезд как проявления вспышечной активности обсуждены в пользу вспышечной активности как критерия принадлежности к звездным системам.

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