SYMPOSIUM IAU No 67

"THE VARIABLES IN RELATION TO THE EVOLUTION
OF STARS AND STELLAR SYSTEMS"

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The problem of origin and evolution of stars has for long engaged the attention of researchers, and papers dealing with the problem have been growing in number.

In the meantime two distinctly different approaches to the problem of origin and evolution of stars have come to the fore[1].

In most writings a purely theoretical (speculative) method has been applied to determine the ways of stellar evolution. The theoretical method is based on the construction of conceivable models of stars and the estimation of changes of their parameters in time [2-5]. It is postulated that in the initial stages of growth, before the stars had reached the main sequence on the Hertzsprung-Russel diagram, the evolution of stars was due to the gravitational condensation of diffuse matter in stars, accompanied by the conversion of gravitational energy into stellar radiation [4,5]. Subsequently, after the stars had reached the main sequence, stellar evolution was due to thermonuclear reactions taking effect within the stars as sources of energy emitted by the stars [2,3].

Thus the theoretical approach is based on two principles:the formation of stars as a result of the condensation of diffuse matter, their radiation being of gravitational nature before reaching the main sequence, and the thermonuclear nature of sources of the stellar energy after the above sequence had been attained.

Despite the fact that certain works in this direction are quite valuable, both hypotheses lying at the base of this direction are far from being manifest,and they lack substantiation.

On the other hand, since astrophysics is foremost of all a science of observation, it is natural to call for the determination of the regular features in the origin and evolution of stars based on a synthesis and a meticulous analysis of observational facts.In time of such synthesis and analysis of facts of observation it is highly desirable to make the least possible number of hypotheses that might predetermine the conclusions on the regular processes going on during the origin and evolution of stars.

The formulated principles define the <u>observational approach</u> to the problem of origin and evolution of stars[1].

The above two approaches are applicable particularly in determining the ways of the growth of stars in the early stages of their evolution.

Here we should like to dwell on the UV Ceti type flare stars as well as on those met with in open clusters and stellar associations. This means that we are concerned with the evolution problems of stars with the small mass (dwarfs with a mass less than $1M_{\odot}$).

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The discovery and investigation of stellar associations,physical systems of recently originating young stars[6-8], have made it possible to reveal a number of regular features in the process of star formation relying exclusively on observational data.It has been found out, for instance, that stars originate together, in groups. As to the group origin of stars this is a significant proposition left out of account by the representatives of the theoretical approach,which has greatly fostered the study of the early stages in the evolution of stars.

The exploration of T-associations, made up of young T Tauri type dwarf stars, has led in particular to the conclusion[6-8] that in time of their origin those stars appear in various parts of the main sequence.

Observational facts testify to active dynamic processes going on in the photosphere,chromosphere and generally in the outer layers of young dwarf stars [8-11].

In the earliest phases, with a duration of 10^6 years,this is a variability of the RW Auriga type,quite often accompanied by chromosphere activity, characterized by the occurrence of emission lines and ultraviolet continuous emission in the spectrum (spectrum of the T Tauri type). There is good reason to assume that this continuous emission is of non-thermal nature,while the energy sources giving rise to emission spectra and producing irregular changes of the radiation of the above stars,occur or appear from time to time in the outer layers[8-13].

In the evolution of dwarf stars flare activity appears in the next stage with a duration of the order of 10^7-$5 \cdot 10^8$ years and depending on the stellar mass.Observational evidence is available to the effect that the RW Auriga type variability stage and that of the flare activity (UV Ceti stage) are mutually overlapping. Thus,for instance, the statistics of flares of some sample of RW Auriga variable stars in the Orion association showed [14] that flare activity arises only at a later phase of variability.

Transitions from a state of low luminosity to one of higher luminosity over a long period, observed in fuors [11,15,16] and Herbig-Haro objects [9,11] are met with comparatively rarely,but they are likely to be activity forms of no lesser consequence in dwarf stars of evolutional value. It should be noted that none of those forms of activity, observed in the early evolutionary stages of the stars, has been predicted or even explained, at least somewhat reasonably, by theoreticians whose views were founded on the hypothesis of the condensation of young stars from diffuse matter. Meanwhile the existence of the above forms of activity is the basic characteristic of those stars.

To study in detail the nature of physical processes going on in flare stars and to make a more direct investigation of the nature of flares, it is more advisable to focus attention on particular M0e-M6e type flare stars in the vicinity of the Sun [17-19].

Some aspects of this problem are treated in our survey paper at the Bamburg colloquium on variable stars [16].

To investigate the evolution of the flare activity and to derive statistical regular features it is advisable to concentrate first of all on flare stars in stellar aggregates:associations and clusters.

The discovery of the first flare stars in the ~~steller~~ association(Orion), which confirms the affinity of these stars with those of the T Tauri type predicted earlier [9],was made by Haro and coworkers [20].

Later flare stars were discovered also in relatively older stellar clusters [21].

Already the first investigations of flare stars in associations and young stellar clusters have made it possible for Haro [21-24] to establish a number of regular features:

1.All stellar aggregates, of the order of 10^8 years or less, contain flare stars.

2.In every aggregate some spectral type Sp_0 can be discerned which delimits the lower part of the main sequence, where flare stars occur, from the upper that lacks flare stars. The latter region corresponds to spectral types earlier than Sp_0. The boundary absolute magnitude M_0 can also be referred to.

3. As we proceed from younger to older aggregates this boundary type of Sp_0 shifts to later spectral types. In older clusters the flare stars are met with only in the M type. The changes of Sp_0 bring about a corresponding change in the boundary absolute magnitude of M_0.

It should be pointed out that the determination of the boundary spectrum of Sp_0 depends on the method of observation, or rather on the minimum amplitude of the flare, still detectable when this method is applied. Therefore while comparing the statistics of flare stars and flares in various aggregates one should make use of data derived from identical observational methods or make corresponding corrections.

The regular features formulated above assume the following simple interpretation: having gone through the T Tauri stage of evolution, or still in the last phase of that stage, all the young newly-formed stars step into the stage of flare activity [14]. The larger the mass of the originating star, the shorter the duration of the stage in which the star is capable of displaying photographic flares (the amplitude of the star discovered by the photographic method exceeding $0^m.6$). In other words, the evolution rates of the star is determined, as expected, by its mass.

The first estimation of the total number of flare stars in the Pleiades, based on the statistical study of well-known flare stars, comes as a telling argument in favour of the above interpretation of Haro's conclusions, confirmed by the observations of

Rosino and co-workers [25].

Let us give a brief description of the method used for this purpose [26,27].

One can get the estimation of the total number of flare stars in some system provided the following two assumptions are made:

1.The sequence of flares in each flare star is a random process described by Poisson's law.

2.The mean frequency of flares in all flare stars of the given system is the same.

It is not hard to show in this case that the number $n_{\bar{k}}$ stars of the system, where $\bar{k}$ flares have been observed, is, with admissible approximation, determined by the expression

$$n_{\bar{k}} = N e^{-\nu t} \frac{(\nu t)^{k}}{\bar{k}!}, \qquad (1)$$

where N is the total number of flare stars in the system, ν is the mean frequency of flares and t is the total effective time of all the observations of the system.

Equation (1) enables us to express the number n_0 of those flare stars of the system that have not been observed in the flare as yet, by means of the numbers n_1 and n_2 of well-known flare stars in which one and two flares have already been observed, respectively

$$n_0 = \frac{n_1^2}{2 n_2}. \qquad (2)$$

Then the total number of flare stars in the system is determined as the sum of already well-known and yet unknown flare stars

$$N = \sum_{\bar{k}} n_{\bar{k}}. \qquad (3)$$

It should be added that the first of the assumptions made is quite well-founded. The possibility of expressing the sequence of flares in particular stars through Poisson's law has been confirmed for instance, in the paper of B.S.Oskanian and V.Yu.Terebizh [28] based on an investigation of the long series of photoelectric observations of some UV Ceti type flare stars in the vicinity of the Sun. Besides, there are additional reasons thanks to which the number of observed flares must be completely in line with Poisson's law. It is as a result of the lack of continuity in the observations of flare stars and their almost random distribution in time, determined by factors independent of the flare star (time of the year, time of the day, weather, time assigned to such observations to be made on the telescope, etc.), even an incompletely random distribution must reach that of Poisson, i.e. the probability of observing k flares for an effective time of observations t for every star can be expressed by the law (1) with a high degree of approximation.

As to the second assumption one can give it up. However, when the mean frequencies of flares are varying in different flare stars in the system, equation (2) turns into an inequality and the application of (2) gives but the lower limit of the number n_0.

In this more general case we have [27]

$$\frac{n_1^2}{2n_2} \leq n_0 \leq \frac{n_1^2}{n_2} \qquad (4)$$

and the formula (1) is replaced by the equation

$$n_k = \sum_i N_i e^{-\nu_i t} \frac{(\nu_i t)^k}{k!}, \qquad (5)$$

where i is the number of groups with different mean frequencies of flares, while N_i and ν_i form, respectively, the total number of flare stars ~~in~~ and the mean frequency of flares in the given group.

Finally, formula (1), applied for k =1 and k =2, makes it possible to determine the mean frequency of flares for the given aggregate of flare stars on the basis of well-known n_1 and n_2:

$$\nu t = \frac{2n_2}{n_1}. \tag{6}$$

The first estimation of the total number of flare stars in the Pleiades was made in 1968 [26] by means of the expressions (2) and (3). It was established that the Pleiades cluster must contain at least several hundred flare stars. Soon, the flare stars in this system turned out to possess dissimilar mean frequencies of flares. Subsequently more precise estimates of the total number of flare stars in the Pleiades were based on the representation of numbers n_k observed by the formula (5) when $i = 2$ [27,29-31].

Since this comparatively young cluster (of the order of $20 \cdot 10^6$ years [32]) is relatively close to us and is very rich in flare stars, it was selected for further detailed study by the photographic method, with the help of wide-angle Schmidt cameras. Owing to the program of observations, carried out jointly by the Tonanzintla, Byurakan, Asiago and Budapest observatories, the number of well-known flare stars in the Pleiades region has exceeded four hundred [31].

A study of the Pleiades based on the results of those observations has led to the following conclusions [27,29-31] :

1.The number of photographic (i.e. showing flares with a photographic amplitude exceeding $0^m.6$) flare stars in this system is of the order of one thousand.

2.The mean frequencies of flares in various flare stars in the Pleiades are generally different; most of them, however, have one photographic flare in about 3600 hours.

3.With the decrease of luminosity in normal condition, outside the flares (in a minimum brightness), the mean frequency of observed flares increases.

4. If the density of the number of flares, going on over some long period of time (for deriving more real statistics), is to be introduced, such density shows a minimum in the central region of the Pleiades. This is due to the fact that stars occurring in the central part of the cluster show lower mean frequencies of flares. This circumstance should probably account for the rarefied cavity, discovered earlier, in the space distribution of well-known flare stars in the Pleiades [33].

5. The absolute number of flare stars, per unit interval of magnitude, increases toward low luminosities and attainst a maximum in the interval of absolute photographic magnitudes M_{pg} =12.0-12.5, whereupon it begins to decline. For $M_{pg} > 13.5$ which corresponds to the visible photographic magnitude +19.0, at some distance of the Pleiades, one cannot be certain that an appreciable number of the members of the Pleiades cluster might occur among flare stars. In other words, beginning with M_{pg}=+19.0 (in the minimum), the number of flare stars observed in the region of the Pleiades is so small that they are hard to distinguish from the stars of the background.

Let us consider some of those conclusions in greater detail.

The first of them, relating to the abundance of flare stars in the Pleiades, as compared with the existing views on the total number of stars in this cluster, can be taken as a telling argument supporting the fact that <u>the stage of flare activity is the</u>

regular stage in the evolution of stars which all the dwarf stars go through. This major conclusion testifies to the fact that flare activity constitutes a typical feature in one of the earliest stages of the evolution of dwarf stars.

In our earliest publications on those matters we drew the conclusion [26,27] that all the stars of the Pleiades, with a visible photographic magnitude > 14.3, are likely to be flare stars. However, the conclusion proved to have been a hasty one. The estimation, based on the application of formulas (2) and (3), of the total number of flare stars among the physical members of the Pleiades (those stars being singled out by Hertzsprung et al [34]), possessing visible photographic magnitudes, ranging from $14^{m}.5$ to $16^{m}.0$, indicated [29,30] that but a little more than half of them turned out to be flare stars in time of the observations (this does not mean, however, that flares were observed in all of them, since the total number of flare stars N includes also the number n_0 of those flare stars in which no flare has been observed).

On the other hand the percentage of flare stars in the interval of photographic magnitudes $13^{m}.0 - 14^{m}.5$ ~~has~~ is, at any rate, ~~been~~ much less than 50 per cent. If we assume that when $\bar{m}_{pg} > 16.5$ again only half of the members of the Pleiades flares up, the total number of the members of the Pleiades will prove of the order of 2000, which is exceedingly high. It is therefore very likely to conclude that the precentage of stars, having flares in time of the observations, goes up with the increase of $\bar{m}_{pg}$ and when $\bar{m}_{pg}$ ~~is round~~ $\sim 18^{m}$, it amounts to nearly 100 per cent. Of course we refer throughout to stars capable of producing photographic flares.

As to the mean frequency of flares, it should he noted that though most stars in the Pleiades display, on the average, frequencies of flares close to each other, still the maximum and mean values of observed frequencies differ by one order. The number of flare stars grows sharply with the decline of the mean frequency.

Further, the fact of increase of the mean frequency of flares during transition ~~of~~ to flare stars of low luminosit~~y,~~ies, substantiated by data given in Table 1 (n is the number of well-known flare stars), can readily be accounted for if we assume that the true frequency of flares with an energy surpassing the assigned E_0, and the distribution of flares according to the energies for flare stars of different luminosities are identical, or that the mean energy of flares during transition to stars of high luminoity grows, at any rate slower than the luminosity proper. In both cases at the same low limit for photographic amplitudes of flares ($> 0^m.6$) in faint stars, we are to observe considerably more flares. This follows namely from data of Table 1 .

Table 1

m_{pg}	n	n_1	n_2	νt
13.0–14.0	12	9	2	0.44
14.0–15.0	30	14	4	0.57
15.0–16.0	57	27	8	0.59
16.0–17.0	73	38	17	0.90
17.0–18.0	109	68	14	0.41
18.0–19.0	88	44	20	0.91
19.0–20.0	31	16	7	0.88

Thus in no way does it follow from the observed growth of the mean frequency of flares with a decline of luminosity that the faint flare stars possess higher flare activity than the bright ones. The higher flare activity observed in faint stars can be due only to the fact that flares of weaker energy can be observed in those stars.

The data on the mean frequency of flares in the same stars, this time referring only to flares with similar energies, confirm this fact.

Taking as a low limit of energy the energy of a flare of photographic magnitude m_{pg}=14.0 and considering all the more powerful flares, we obtain the figures listed in Table 2 (the second column offers the corresponding mean boundary amplitudes for the given interval of m_{pg}).

Table 2

m_{pg}	Δm_{pg} (min)	n	n_1	n_2	νt
13.0–14.0	0.53	8	6	2	0.67
14.0–15.0	1.03	14	10	4	0.80
15.0–16.0	1.75	7	6	1	0.33
16.0–17.0	2.6	8	7	1	0.29
17.0–18.0	3.6	12	10	2	0.40
18.0–19.0	4.5	14	12	2	0.33
19.0–20.0	5.5	6	6	0	<0.33

In spite of some uncertainty due to inadequate statistics, the data of Table 2 apparently attest that there occurs in this case even a weak decline of the mean frequency of flares with identical energies as the luminosity diminishes. This decline may be due both to a simple decrease of the frequency, with the distribution of the energy values remaining invariable, and to the slow decline of the mean energy of flares as the luminosity of flare stars decreases.

To solve this problem we divide the flares included in the statistics of Table 2 into two groups according to the energies, the first group comprising flares with amplitudes ranging from $\Delta m_{pg}(min)$ to $\Delta m_{pg}(min)+1$ and the second group - flares with amplitudes $>\Delta m_{pg}(min)+1$. We obtain the following distribution of flares by those groups (Table 3).

Table 3

m_{pg}	Group I	Group II	All the flares
13.0–14.0	9	1	10
14.0–15.0	16	5	21
15.0–16.0	7	1	8
16.0–17.0	8	1	9
17.0–18.0	10	4	14
18.0–19.0	15	1	16
19.0–20.0	4	2	6
	69	15	84

The ratio of the number of flares in the second group to that of flares in the first group shows, within accuracy limits, no regular changes with variations of the luminosity. This means that the second of the above possibilities stands closer to reality. It is interesting to note that on the average nearly 80 per cent of all the flares ~~are~~ brighter than the conventional boundary energy m_{f} =14 does not exceed in energy this boundary more than 1^{m}, while the more powerful flares form but one-fifth part. This gives some idea of the "luminosity function" of large flares.

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From among the closest clusters, after the Pleiades, the Praesepe cluster is relatively well studied in respect of flare stars. At present we are already familiar with thirty flare stars of this region.

As the distance of the Preasepe cluster differs but little from that of the Pleiades, a comparison of the data on flare stars for those two systems should be of definite interest.

Estimates of the total number of flare stars in the Praesepe system, based on the statistics of flares observed up to now in that region, indicate that the Praesepe cluster contains upwards of 150 flare stars capable of photographic flares. Thus the total number of flare stars in Praesepe is considerably less than the total number in the Pleiades.

In contrast to this, statistical estimates show that the mean frequency of flares in the Praesepe cluster is somewhat higher than in the Pleiades.

Finally, as in the Pleiades so in the Praesepe cluster the absolute number of flare stars, per unit interval of magnitudes, grows with the decline of the luminosity. In this case, too, the maximum of the absolute number of flare stars is achieved in the interval of photographic absolute magnitudes M_{pg}=12.0-12.5. With transition to lower luminosities the number of flare stars drops sharply, and doubts arise as to whether they belong to the cluster.

Though the number of flare stars so far well-known in Praesepe is not large enough for reliable statistics (the total duration of all observations in the Pleiades comes nearly to 2300 hours and that of Praesepe - about 400 hours), nevertheless we are inclined to believe that the above differences between the systems of the Pleiades and Praesepe are real.

The determination of the initial luminosity function, i.e. the luminosity function of originating stars, is of cardinal significance to the problem of stellar evolution.

As mentioned above, the percentage of flare stars among the rather faint members of the Pleiades is close to one hundred. Assuming that the same holds also for other not too old clusters, we can determine as the first approximation the quantity of the very faint members of clusters finding out the total number of flare stars.

This offers the chance of determining the number of very faint stars in corresponding clusters.

Since the number of bright stars in those clusters is well known from their proper motions, this gives the opportunity of deriving certain ~~evidence~~ information on the initial luminosity function of the clusters. As to the absolutely faint stars (M_{pg}=12 and weaker) relevant information is expected to be obtained from the statistics of the faintest flare stars in the systems under consideration.

With this aim in mind let us estimate the ratio of the total number N_B of bright stars, that usually do not undergo the phase of flare activity, their luminosities included in the interval

$M_{pg} = +2 \div 4$ (we take an interval where the stars are still in the main sequence), to the total number N_f of flare stars, possessing absolute photographic luminosities, $M_{pg} = +10.5 \div 12.5$ in the minimum brightness in the clusters Pleiades and Praesepe under review. Here we take flare stars so faint that they could barely quieten in the lifetime of Praesepe, all the more so for the Pleiades. We have borrowed data on the bright stars of the Pleiades and Praesepe, required for the given purpose, from the catalogs of E. Hertzsprung and co-workers [34] and G.Vanderlinden [35] ,respectively, while the estimates of the total number of the flare stars of the above luminosities in those systems have been obtained from the figures quoted in the card-index of flare stars compiled in Byurakan. The results of determining the corresponding numbers and their ratios are listed in the following table :

Table 4

Parameter	Pleiades	Praesepe	Hyades	Coma Berenices	References
$m - M$	5.5	6.0	3.0	4.5	[36]
N_f	363	73	37	11	[24,31,40,41]
N_b	31	43	26	10	[34,35,37,38]
N_f / N_b	11.7	1.7	0.7	0.9	

It follows from the figures in Table 4 that the ratio of the total number of flare stars to that of bright, non-flaring stars, with their luminosities ranging over appropriate intervals,is one order larger in the cluster Pleiades than the same ratio for the cluster Praesepe.

It can be readily proved that this is not due to the difference in the ages of those clusters. In effect, the luminosity intervals for non-flaring and flare stars are chosen, as mentioned above, in such a way that in the former case bright stars, still in the main sequence and in the latter case stars still retaining their flare activity correspond to those intervals, irrespective of differences in the ages of the clusters. Therefore the differences observed in the magnitudes of those ratios should be regarded as a direct evidence of the differences of the initial luminosity functions of the Pleiades and Praesepe clusters, since in case of similar initial luminosity functions we should have an identical magnitude of the ratio in question.

It should be added that scantier and less reliable facts in flare stars in the Hyades and Coma Berenices clusters, listed in the Table, indicate a magnitude of the order of a unit for the ratio N_f/N_b, i.e. the initial luminosity function of those clusters differs but little from the initial luminosity function of the cluster Praesepe.

Naturally the assumption to the effect that all stars or at least most of the stars of the clusters under consideration, with absolute magnitudes ranging from $10^{m}.5$ to $12^{m}.5$, display flare activity, needs verification. Such assumption is favoured by the treatment of stars of the main sequence, in the same interval of absolute magnitudes in a volume with a radius of 10 parsec around the Sun.

Out of sixty-five such stars flare activity has been detected in only six of them. However, one should take into account the fact that any long tracking was conducted only for a number of the remaining fifty-nine stars. That is why the percentage of flare stars in the above group can approximate fifty. Since objects older than the Pleiades and Praesepe are surely to occur among stars in our vicinity, most stars of the same luminosity interval in the above clusters are expected to be flare stars.

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We stated above a number of results of the statistical investigation of flare stars in clusters, which are of considerable interest to the problem of the evolution of dwarf stars.

Our primary concern in further studies should be an extension of the scale of observations ~~aso as~~ to cover all the nearest clusters, including the older ones, of the order of 10^9 years.

New observations will favour the final solution of the problems dealt with in the report, as well as those left out of account through the lack of necessary observational data.

It is very important, for instance, to find out whether flare stars of very low luminosity $(M_{pg} > 15)$, reminding one by their luminosity of the UV Ceti type stars around the Sun, occur in associations and clusters, specially in the Pleiades. The scanty observational data available testify apparently to the lack of very faint stars of the T Tauri type in the Orion association. The problem of a possible ~~ratio~~ connection of those phenomena is of definite interest.

From this viewpoint as well as in order to investigate the impact on the results of statistical estimates,relating to flare stars in stellar aggregates, particularly on our results, it is expedient to make a comparative study of flare stars in stellar aggregates and in the surrounding galactiv field (among the stars of the background).

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