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ROSAT OBSERVATIONS OF PLEIADES FLARE STARS

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The X-ray data of a sample of 104 flare stars (FSs) in the Pleiades cluster region obtained by Stauffer et al. [1] on the basis of deep *ROSAT* PSPC observations are analyzed. If divide the X-ray detected in late-type stars of the Pleiades cluster into FSs and non-FSs, one finds that X-ray luminosities of stars of both groups can be considered as drawn from the same parent population. Moreover, in order to classify stars in sample of 23 late-type Pleiades stars of unknown nature discriminant analysis in a four-dimensional parameter space (log (L_X), log (L_X/L_{bol}), and *ROSAT* hardness ratios HR1 and HR2) have used. It can be shown that the majority of these stars (16) are very probably FSs rather than non-FSs.

1. *Introduction.* The discovery and study of red dwarf flare stars (FSs) in the solar vicinity and in star clusters and associations had a fundamental significance for the study of the physics and evolution of red dwarf stars. FSs were discovered in 1949 in the solar vicinity and named UV Cet type variables (classical FSs). The quiescent radiation of these stars is interrupted by randomly distributed flares. UV Cet type stars have very low luminosities and are seen in the vicinity of the Sun.

In 1954 Ambartsumian, [2] while analyzing the problem of the nature of continuous emission in the spectra of T Tauri type stars (TTSs), called attention to the unusual observational fact that continuous emission also arises in the spectra UV Cet type stars in the vicinity of the Sun during their brief flares, which at this period acquire properties that are at different stages of light variation in TTSs. This suggests a common nature of physical processes observed in the classical FSs and TTSs. It served as basis for the conclusion that TTSs and classical FSs are related objects.

This idea was strengthened by the discovery of several FSs of comparatively higher luminosity in a very young stellar system - the Orion association (Haro & Morgan [3]). Subsequently, several dozen FSs were detected in the associations of Orion, Monoceros, Taurus Dark Clouds (Haro & Terrezas [4]; Haro [5]; Rosino [6-7]).

The discovery of FSs in these young systems showed that besides the old classical FSs in the vicinity of the Sun there also exist young FSs. Haro [8] suggested that the stage of flare activity is an evolutionary stage of red dwarfs which follows the TTSs stage.

Of decisive significance in the confirmation of this fundamentally new idea was the accidental discovery by Johnson & Mitchell [9] of the first flare star in the Pleiades cluster, which is of age 7×10^7 years, an order of magnitude larger than the age of the Orion association, and does not contain any TTSs. These discovery initiated new, photographic observations of the regions of the stellar clusters, which led to the discovery of FSs, not only in the Pleiades, but also in the older clusters of the Praesepe and Hyades.

They showed that FSs representing a certain stage of evolution of red dwarf stars, or at least a certain portion of them, occuring in systems of very different ages. Moreover, while in the young systems (associations) the FSs coexist with TTSs, in older systems, where there are no TTSs, they constitute the most numerous population.

Strong X-ray emission is an important characteristic of pre-main sequence stars (PMSs). Observations with *EINSTEIN* satellite in the Orion Star Forming Region (SFR) indicate that many X-ray sources can be identified with young stars (Ku & Chanan [10]) with luminosities three or four orders of magnitude greater than the solar X-ray luminosity ($L_{X\odot} \approx 10^{26} - 10^{27.5}$ erg/s during the 11-year activity cycle). Also, the observations with *EINSTEIN* in many other SFR's revealed a substantial number of previously unrecognized PMSs (Walter et al. [11]; Feigelson [12]). Hundreds of such sources have been detected in Orion, Taurus-Auriga and other SFRs (Pallavicini [13], references therein).

The launch of the *X-ray Observatory ROSAT*, which has a much higher sensitivity than the *EINSTEIN* satellite in the soft band (0.1-2.4keV), has opened a new opportunity in the search for X-ray emitting PMSs. *ROSAT* carried out an all-sky survey which allows the investigation of the spatial distribution of X-ray sources in selected areas of the sky, and in particular in star clusters and associations.

Taking advantage of the *ROSAT* capabilities (Pfeffernan [14]; Trümper [15]), a project was started with the aim to study SFRs in X-rays (Krautter et al. [16]). Here we report the results of the identification and study FSs in the Pleiades cluster region.

2. *FS stage as an obligatory stage in the life of red dwarf stars.* Various observational facts suggest that the mean lifetime of FSs, or the stage of flare activity, is significantly longer than the duration of the TTS stage, which is in perfect accord with the conjecture of Haro [8,17] that the stage of flare activity follows TTS stage in the life of red dwarf stars.

In the connection with this conjecture the question naturally arises:

Is the FS stage a regular evolutionary stage through which all red dwarf stars pass, or are there different evolutionary paths for these stars?

In 1968 Ambartsumian [18] developed a simple statistical method that makes it possible to estimate the total number of FSs in any system once a certain number of stars of that class have been detected in it.

The total number of unknown FSs in the system is determined by the following formula:

$$n_0 = \frac{n_1^2}{2n_2}, \qquad (1)$$

where n_1 and n_2 are numbers of FSs observed to have flared up once and twice respectively.

This formula was obtained under two assumptions: the distribution of flares is random in time for each flare star, the mean frequency of flares is the same for all FSs of a given system and the result obtained corresponds to a lower limit for the required total number of FSs in the systems. The upper limit for the total number FSs does not exceed the lower limit two time.

Applying this formula to the FSs known at that time in the Pleiades cluster, Ambartsumian [18] obtained a value for the total number of FSs in this system, which respect to order of magnitude of all faint stars in this cluster. On this basis the completely unexpected but fully justified conclusion was reached:

1. *All or almost all of the faint stars in the Pleiades cluster are FSs.*

2. *FS stage (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.*

Observations of low-mass stars in the Galaxy allow to outline the evolutionary path of red dwarf stars. The main results were presented by Haro & Chavira [19]; Ambartsumian & Mirzoyan [20,21]; Haro [22]; Appenzeller [23]; Mirzoyan [24]. Here we give some, partially new, observational results, which confirm the evolutionary concept of red dwarf stars.

TTSs and FSs have physical and dynamical similarities: they coexist in stellar associations (Haro & Chavira [19]; Rosino [6]); characteristic features of TTSs like continuous emission appear distinctly in FSs, usually during flares (Ambartsumian [2]); some TTSs show flares (Haro & Chavira [19]; Rosino [7]; Appenzeller & Mundt [25]); multiple stars of the Trapezium type are known to consist of combinations of TTSs and FSs (Hambaryan [26]).

A characteristic property shared by TTSs and FSs is the occurrence of flares, i.e. short time brightness outbursts with a rapid rise and a slower decline. Although in individual observed TTSs flares seem to occur less frequently than in classical FSs, the properties of the TTSs flares observed in UV and visual wavelengths (see e.g. Kylyachkov & Schevchenko [27]) at X-rays (Feigelson & De Campli [28]; Montmerle et al. [29]; Walter & Kuhi [30]), and radio wavelengths (Feigelson & Montmerle [31]; André et al. [32]; Stie et al. [33]; Feigelson [34]) agree well with those found for FSs. Flares are known to occur in all subclasses of TTSs, in classical TTSs (such as DG Tau and RW Aur) as well as in weak-line TTSs. An additional indication for a connection between FSs and TTSs is the occurrence of spectral signatures typical for stellar flares in shortterm emission line variations of classical TTSs. These results indicate a physical and evolutionary connection between TTSs and FSs.

However, TTSs, perhaps, present the first stage of evolution of red dwarfs after formation and therefore, among the empirical properties which are observed for TTSs, but not in classical FSs, are strong, cool, and sometimes surprisingly well collimated stellar winds or outflows (cf. e.g. Lada [35], Mundt [36]; Appenzeller & Mundt [25]).

Another major difference between these two types of objects cool dusty circumstellar envelopes (cf. Lada [35]; Appenzellar & Mundt [25]; Beckwith et al. [37]) observed at TTSs. In the case of classical FSs, we have no evidence for either cool circumstellar disks or outflows.

FSs in star clusters and associations and UV Cet stars in the solar vicinity are objects of the same physical class, as indicated by their observed properties like light curves, colors, and spectra (Mirzoyan [38]). In the light of the formation of FSs in stellar clusters and associations the existence of UV Cet-type stars in the vicinity of the Sun can have two explanations.

According to the first explanation, proposed by Ambartsumian [39], these stars were formed in a system that still exists. In other words, UV Cet-type stars in the vicinity of the Sun constitute a physical system at present.

The second explanation, advanced by Herbig [40], assumes that UV Cet-type stars were formed in systems that have now decayed and appeared in the vicinity of the Sun accidentally, after decay of the "mother" systems as result of their spatial motion.

As appears now that UV Cet stars of the lowest luminosities are distributed uniformly in the galactic disk (Mirzoyan et al. [41]), after the disintegration of their "maternal" systems.

The discovery of TTSs with flare activity showed that both evolutionary stages are overlapping (Ambartsumian [42]). An intermediate stage may be the weak-line TTSs.

The coexistence of young FSs with TTSs in stellar associations, and the existence of comparatively old FSs in star clusters and the general field where TTSs are absent, show that flare stars very likely represent a later evolutionary phase of low-mass stellar evolution. The observational data indicate that all FSs originate in star clusters and associations. Young and middle ages FSs of comparatively high luminosity are observed in star clusters and associations where they originated. Their flare activity can be considered as a criterion for their membership in young systems (Mirzoyan et al. [43]). Old FSs of low mass kept their flare activity because of their slow evolution (small masses).

They are mainly observed in the general galactic field, after disintegration of their "maternal" systems. Kunkel [44] has shown that the duration of flare activity stage for stars of absolute magnitude $M = 15$ amounts to some billion years.

The observed space distribution of FSs of different masses in the Galaxy is thus a natural consequence of their different ages and the increase of duration of the flare activity stage of evolution towards FSs of lower masses (Mirzoyan [38]).

On the basis of all these observations, the probable evolutionary path of red dwarf stars is as follows:

classical TTSs - weak-line TTSs - FSs - classical FSs - red dwarf stars constant radiation.

3. *X-ray observations of the Pleiades cluster.* The Pleiades is an important laboratory for the study of main-sequence stellar evolution because of its relatively youth and proximity.

Photographic observations with wide-field telescopes of FSs in the Pleiades cluster have been carried out since 40 years. More than 500 FSs were found in the system.

Haro ([45,46]) and Haro & Chavira [19] have shown that in every stellar system there is a boundary spectral class (luminosity) which divides all stars of the system into two groups: FSs and non-FSs. The limit shifts towards later spectral classes (lower luminosities) when older systems are considered.

In this context it is interesting to consider the observational data of FSs in X-ray of this subsystem.

With an estimated age ~ 70 million years and at a distance ~ 127pc, a large number of intermediate and low-mass cluster members are detectable with X-ray telescopes.

In the Pleiades cluster, there have been several extensive X-ray studies based on *EINSTEIN* Observatory data (Caillault & Helfand [47]; Micela et al. [48]). The most extensive compilation of *EINSTEIN* data reports a total of 85 Pleiades member stars as X-ray sources, and upper limits of X-ray emission for a further 198 members stars (Micela et al. [49]).

Recently, three surveys of the Pleiades cluster in the X-ray regime have been carried out using *ROSAT* observations: the first is based on data collected during the *ROSAT* Allsky survey (Schmitt et al. [50]), the second is derived from a set of 3 pointed exposures (Stauffer et al. [1]) and the third from a single pointed observation (Micela et al. [51]).

The first survey detected X-ray emission for 28 Pleiades stars, while in the second studies a total 317 X-ray sources were reported, 171 of which could be identified with certain or probable Pleiades members. In the third survey of 214 Pleiades stars 99 were detected in X-rays, and upper limits for the remainder were presented.

For the study of FSs in the Pleiades region we used data from Stauffer et al. [1], based on their three *ROSAT* PSPC observations of the cluster.

One field is roughly centered on the Pleiades, a second field is offset ~ 30 arcminutes to the northeast, and the third field is offset ~ 40 arcminutes to the northwest of the center.

These observations compound approximately one quarter part of the wide-field optically studied region and summarized in Table 1.

Table 1

RESULTS OF *ROSAT* PSPC OBSERVATIONS OF FSs IN THE PLEIADES CLUSTER

Membership	X-ray Sources		FSs		
	Detected	Identified	Known	Identified	dK-dM
Members	-	171	167	81	32
Non-members	-	15	99	23	13
Total	317	186	266	104	45

In Table 2 and Figs. 1a-1d we present descriptive statistics and histograms as a function of visual magnitude of detected and non-detected subsamples of FSs Pleiades cluster using X-ray data from Stauffer et al. [1]. As appeears

Table 2

RESULTS OF DESCRIPTIVE STATISTICS DETECTED AND NON-DETECTED FSs IN X-RAYS BY *ROSAT* PSPC OBSERVATIONS

Detection	No. of FSs	Visual magnitude		Color index		Number of flares		Mem. prob.	
		$<V>$	σ	$<V-I>$	σ	$<k>$	σ	$<M.P.>$	σ
Detected	81	15.04	1.54	1.86	0.58	3.99	2.88	0.81	0.12
Non-detected	86	16.80	1.90	2.20	0.73	2.94	2.74	0.80	0.11
Detected	22	16.33	1.52	2.18	0.55	4.00	3.39	0.10	0.14
Non-detected	76	16.21	1.31	1.60	0.82	1.68	1.34	0.04	0.10

from the data of Table 2 non-detected members, in average, are fainter than detected cluster members. It indicates that X-ray luminosity might be correlated with visual luminosity.

However, the comparison of Figs.1a-1b show that there are many comparatively bright members of FSs in the Pleiades clusters which are not detected in X-rays, whereas a significant number of late type stars yet unknown as FSs were detected as X-ray sources.

Applying, as a first approximation, Eq.1 to the FSs detected in X-ray, for the numbers of lower and upper limits of potential FSs we obtained values of 16 and 32, respectively. It is interesting to note that the estimated number of the upper limit of yet unknown FSs coincides with the number of late type member stars detected in X-rays.

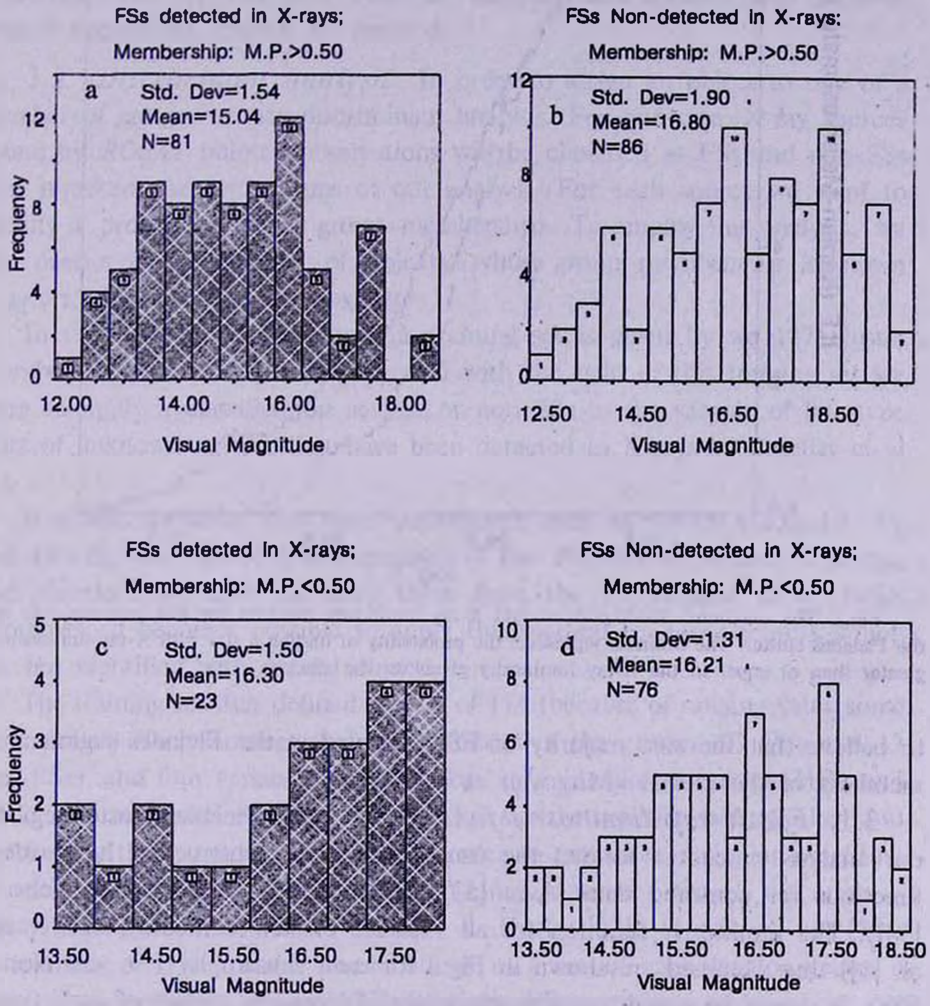

Fig.1. (a) Histogram of the distribution of FSs identified with X-ray sources as a function of visual magnitude (membership probabilities greater than 0.5 on the base proper motion (Stauffer et al [1])). (b) Same as for (a) except for FSs non-detected as X-rays sources. (c) Same as for (a) except membership probabilities less than 0.50. (d) Same as for (b) except membership probabilities less than 0.50.

For the primary purpose of this study - the determination of the X-ray properties of FSs - we wish to restrict ourselves to only high probability cluster members determined by Stauffer et al. [1],[1] although there are some grounds

[1] *Stauffer's et al. [1] membership is based on photometric and proper motion data of stars.*

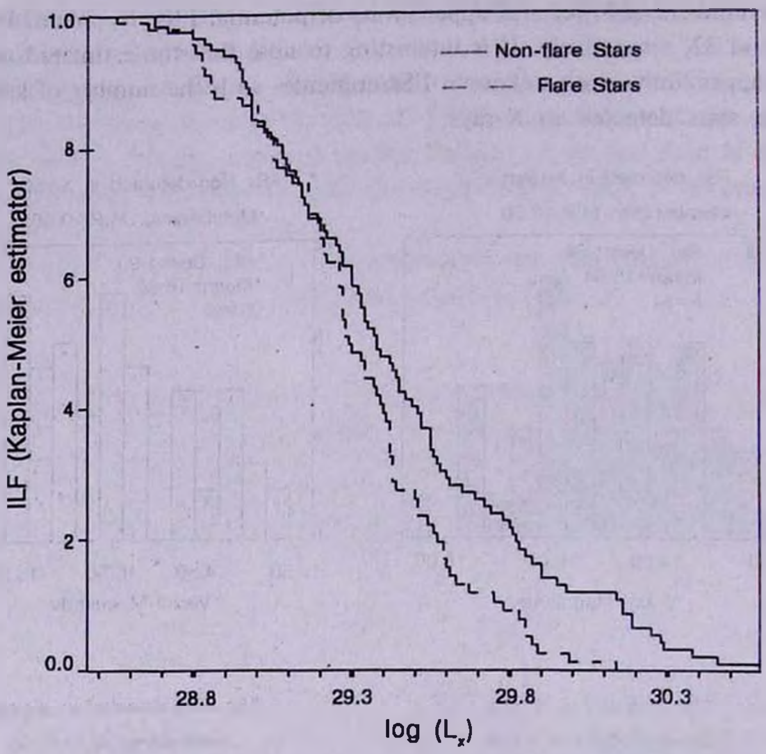

Fig.2. The maximum likelihood integral X-ray luminosity function for FSs and non-FSs in the Pleiades cluster. The ordinate represents the probability of finding a star with X-ray luminosity greater than or equal to the X-ray luminosity given on the abscissa.

to believe that the vast majority of FSs observed in the Pleiades region are members of the cluster (Mirzoyan et al. [43])

3.1. *FSs X-ray luminosity function.* For the Pleiades cluster region our analysis procedure follows the usual method of constructing luminosity functions for censored data (Avni [52]; Schmitt [53]; Feigelson & Nelson [54]). The luminosity function for all Pleiades cluster members (Stauffer et al. [1]) thus obtained are shown in Fig.2 for each subsample (FSs and Non-FSs). It should be noted that the subsample of Non-FSs consist of early type as well as of late type cluster member stars. As we can see form Fig.2, for low luminosities the X-ray luminosity function for FSs and non-FSs almost is the same.

In order to investigate whether this is the case we have proceeded as follows. We have divided all optical members of the cluster in two separate ranges of colors: $(B-V)_0 \le 0.8$ (early type stars) and $(B-V)_0 > 0.8$ (late dG and dK-dM type stars).

We then have divided the sample of late-type stars into FSs and non-FSs, and have applied non-parametric tests for two independent samples. It tests the null hypothesis that two samples are drawn from the same parent population (*goodness-fit-problem*, see e.g. Kendall & Stuart [55]). If the probability is small (0.05 or less is often used), the null hypothesis is rejected. For the five different tests[2] the probabilities range between 23% and 57%, i.e. the null hypothesis that the "FSs" and "non-FSs" samples come actually from the *same* parent population, cannot be rejected.

3.2. *Discriminant analysis*. In order to assign an object to one of a number of groups we use discriminant analysis. For our case, X-ray sources found by *ROSAT* pointed observations will be classified as FSs and non-FSs that represent the two groups of our analysis. For each source we want to specify a probability for its group membership. To employ this analysis, we first need a certain number of projects, whose group membership is known a *priori*, the so-called training set.

In the case Pleiades region this training set is given by we 137 cluster members identified in X-rays [56], and with the held of this training set we want to apply a classification as FSs or non-FSs to the sample of late-type stars of unknown nature, that have been detected in X-rays by Stauffer et al [1].

It should be noted that some parameters, such as optical colors $(B - V)_0$ and $(V - I)_0$, may affect (predetermine) to the Pleiades classification results, and therefore we have excluded them from the list (Gagné et al. [56]). Moreover, it becomes possible to apply this method to X-ray sources which are not identified with optical objects.

The training set thus defined consist of 114 (because of missing value some of variables) X-ray sources that are members of the cluster (72 FSs and 42 non-FSs), and four variables: $\log(L_X)$, $\log(L_X/L_{bol})$, hardness ratios: HR1 and HR2. We standardized each variable by subtracting the mean value and dividing by their standard deviation in order to guarantee a similar weighting of each component in the four dimensional parameter space. We apply a linear discriminant analysis (Murtagh & Heck, [57]; Sterzik et al, [58]) determining the best linear combinations of a set of variables to predict a categorical dependent variable (FSs and non-FSs).

Classification results are given in Table 3 and can testify about the reliability of discrimination procedure. The percentage of cases correctly classified exceeds 99%.

4. *Summary and Conclusions*. Current evidence points towards the conclusion that FSs represent an evolutionary stage of red dwarf stars which

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[2]Gehan's Generalized Wilcoxon test of Permutation Variance; Gehan's Generalized Wilcoxon test of Hypergeometric Variance; Peto & Peto Generalized Wilcoxon test; Peto & Prentice Generalized Wilcoxon test and Logrank test are contained in the ASURV software package; see Feigelson & Nelson [54].

Table 3

CLASSIFICATION RESULTS OF DISCRIMINANT ANALYSIS

Actual group	Number of Cases	Predicted Group Membership	
		Non-FSs	FSs
Non-FSs	42	42	0
FSs	72	1	71
dK-dM	23	7	16

follows the TTS phase, and that all (or nearly all) low-mass stars pass through this stage during their evolution [38,59]. At the age of the Pleiades, FSs probably constitute a large fraction of all low-mass stars.

The flare star phenomenon is therefore of high importance for our understanding of the early phases of stellar evolution. Moreover, the fraction of FSs among a stellar population, as well as the limiting $(B - V)_0$ colour (i.e. spectral type), at which they are found, might serve as an important tracer for the age of field stellar populations, if these quantities are calibrated by open clusters.

As indicated by their X-ray luminosity functions, high levels of coronal activity are displayed both by FSs and non-FSs in the Pleiades. However, using discriminant analysis, we have demonstrated that it is possible to classify late-type stars as FSs or non-FSs with high reliability on the basis of *ROSAT* X-ray data and optical photometry.

Using this method, we could show that out of a sample of 23 late-type Pleiades members of unknown nature, about 16 most probably are FSs, while the remaining 7 stars more likely are non-FSs. This result agrees well with the estimated number of 16-32 potential FSs within this sample, as calculated from the number of X-ray detected FSs.

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ROSAT НАБЛЮДЕНИЯ ВСПЫХИВАЮЩИХ ЗВЕЗД В ПЛЕЯДАХ.

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Анализированы рентгеновские данные ансамбля 104 вспыхивающих звезд (ВЗ) в области скопления Плеяды, полученные Стауффером и др. [1], на основе глубокого PSPC *ROSAT* наблюдений. Если звезды поздних спектральных классов в Плеядах разделить на две группы - ВЗ и не - ВЗ, то находим, что рентгеновские светимости обеих групп можно рассматривать как выбранные из одной родительской популяции. Более того, для классификации 23 звезд поздних спектральных классов неизвестной природы в Плеядах, дискреминантный анализ в четырехмерном параметрическом пространстве (lg (L_X), lg (L_X/L_{bol}), и *ROSAT* индексы жесткости HR1 и HR2) был использован. Можно показать, что большинство этих звезд (16) по всей вероятности являются ВЗ, чем не-ВЗ.

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