FLARE STARS IN THE PLEIADES. II

V. A. Ambartsumyan, A. V. Mirzoyan,
É. S. Parsamyan, O. S. Chavushyan,
and L. K. Erastova

The results are given of observations of flare stars in the Pleiades at Byurakan in the winter of 1969-1970 and partly in the second half of 1970. They are supplemented by observations at Asiago and Konkoly. Of 44 new flare stars, 14 were detected on the plates of the 40", 11 on the plates of the 21" Schmidt telescopes of the Byurakan Observatory, 15 at Asiago, 2 at the Konkoly Observatory, one independently at Byurakan and Asiago, and one simultaneously in the two Byurakan telescopes. The total number of already known flare stars in the region of the Pleiades (16 square degrees) is 208. Some of these are probably not members of the cluster. We have estimated that the lower limit to the number of flare stars in this region is 700. Evidence in favor of strong, but slow, variations in the activity of some flare stars in the Pleiades is given. In the Appendix are given data on flare stars in the Pleiades observed at Byurakan after the paper was submitted.

This paper contains the general results of observations of flare stars in the Pleiades during the Fall and Winter of 1969-1970 and some of the results of observations in the second half of 1970 at the Byurakan Observatory and also at Asiago and Konkoly. As in the first paper in this series [1], some conclusions are drawn about the flare stars in the Pleiades based not only on the Byurakan observations, but also on all the available data on flare stars in this cluster.

1. New Data on Flare Stars in the Pleiades. In Table 1 we give in the usual form data on new flare stars. We continue the system of enumeration begun by Haro and his colleagues [2, 3], continued by us in [1], and again continued by Haro and his colleagues [4, 5]. Apart from our own observations, Table 1 contains data on 16 new flare stars discovered in 1969-1970 by Pigatto and Rosino at the Asiago Observatory [6].* The last star in the list is No. 210, but the number of known stars is less than this by two, since two stars in the list in [1], No. 118 and No. 121, were discovered by Haro a second time and were given the numbers 148 and 152 by him [4]. Obviously, this will be taken into account in publishing the final list of all flare stars.

Up to the present time the total time taken for the observations of flare stars at the Observatories of Tonantzintla, Asiago, Byurakan, and Konkoly is 1303 h. This includes results for observations at Byurakan in this paper, obtained from 80 h of observations with the 40" and 197 h with the 21" Schmidt telescopes of the Byurakan Observatory.

We note also that doubtless some of the 208 flare stars are not members of the Pleiades. For example, it is probable that the star HII 2411 = No. 55 is a member of the Hyades [7]. The problem of projecting flare stars on the background is deserving of detailed study.

*One of these was discovered independently at Byurakan (cf. Note to Table 1).

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TABLE 1. New Flare Stars in the Pleiades

№	Star (HII)	α (1900)	δ (1900)	m_{pg}	Δm_{pg}	Flare date	Tele-scope	Reference cited
1	2	3	4	5	6	7	8	9
167		$3^h37^m.5$	24°34′	19.0	0.9	18.10.68	40″	
168		36.9	25 43	19.5	3.8	19.10.68	40	
169		45.7	21 59	19.5	4.5	20.12.68	21	
170		37.6	22 40	17.0	1.2	15.08.69	40	
171	3133	45.8	23 55	15.8	0.8	15.08.69	40	
172		36.1	22 38	18:?	4.7	11.09.69	24	[6]
173		37.2	22 29	17.0	3.5	11.09.69	40	
174		36.8	23 03	19.6	2.3	11.09.69	40	
175		40.9	24 54	17.5	0.7	15.09.69	24	[6]
176		43.0	24 36	19:	3.5	16.09.69	24	[6]
177		31.0	22 26	15.7	1.6	18.09.69	21	
178		47.1	25 14	17.7	2.7	18.09.69	40	
179		38.6	24 22	18.0	3.2	19.09.69	40	
180		41.0	25 04	17.1	2.1	20.09.69	40	
181		35.1	22 02	17.8	3.3	21.09.69	21,24	[6]
182		46.9	25 01	19:	2.4	4.10.69	24	[6]
183		50.2	25.12	(18	2.3	10.10.69	24	[6]
184		39.3	22 44	18:	2.3	12.10.69	24	[6]
185		42.6	23 40	20.0	4.4	13.10.69	21	
186		41.7	24 09	19:	2.9	14.10.69	24	[6]
187		41.0	22 57	16.5	1.2	15.10.69	24	[6]
188		34.2	24 05	18:	2.5	17.10.69	24	[6]
189		43.3	23 45	16.5	2.8	19.10.69	24	[6]
190		49.7	22 31	16.1	1.3	21.10.69	24	[6]
191		45.6	21 48	17.6	2.2	9.11.69	21	
192		42.8	24 19	20.5	5.7	13.11.69	21	
193		42.8	24 49	16.6	0.5	10.11.69	21	
194		42.2	23 20	20.0	5.2	10.11.69	21	
195	1094	40.7	23 39	14.6	1.4	10.11.69	26	[8]
196		39.3	24 15	17.5	4.0	13.11.69	21	
197		39.9	25 33	17.0	2.1	1.12.69	24	[6]
198		42.2	26 02	19:	5.7	2.12.69	24	[6]
199		41.4	22 03	20.0	5.1U	10.12.69	21	
200	1172	40.9	23 59	15.9	0.7	1.01.70	40	
201		45.9	23 45	18.5:	5.2	1.01.70	24	[6]
202		$3^h39^m.3$	23°03′	19.0	4.0	9.01.70	40	
203		39.8	24 20	17.6	3.3	9.01.70	40	
204		32.0	22 22	(17.5	3.0	3.02.70	24	[6]
205		35.7	24 47	19.4	5.1U	10.09.70	40	
206	1038	32.3	23 15	16.8	0.5	10.09.70	40	
207		42.7	24 42	18.1	2.6	10.09.70	40,21	
208		43.7	24 00	19.4	5.3	29.09.70	21	
209		41.6	25 57	19.4	5.2	30.09.70	21	
210		34.3	22 52	17.8	2.7	9.10.70	26	[8]

Note: 181 – this flare was observed simultaneously at Asiago and Byurakan. 205 – this is the first of two observations of flares at Byurakan. The star is remarkable in that the second flare registered was observed simultaneously on three telescopes (two telescopes at Byurakan and one at Konkoly), a spectral photograph of the flare being obtained on the 40" telescope (Table 2). Attention is drawn to the fact that during one month two flares of so large a magnitude occurred.

TABLE 2. Repeated Flares of Known Flare Stars in the Pleiades

№	Star (H II)	α (1900)	δ (1900)	m_{pg}	Δm_{pg}	Flare date	Telescope	Reference cited
16	1286	$03^h41^m.1$	23°18′	$16^m.4$	$1^m.6$	29.12.69	24″	[6]
25		42.6	21 54	15.2	0.9	27.09.70	21	
36		36.2	23 46	17.1	1.3	14.09.69	40	
					1.0	10.12.69	21	
48	1061	40.6	23 48	15.1	2.7	9.10.70	26	[8]
51	1827	42.4	23 40	15.9	1.3	6.12.69	21	
55	2411	43.7	24 01	15.5	1.4	10.10.69	24	[6]
					0.7	17.10.69	21	
					0.7	9.01.70	40	
					1.0	3.02.70	24	[6]
					0.6	11.10.7,	21	
62		33.9	24 56	16.0	2.1	1.01.70	40	
68	134	37.7	23 55	15.6	4.0	4.09.69	40	
102		34.6	24 50	19.0	3.9	17.10.69	24	[6]
103		36.9	23 08	16.2?	2.5	2.09.70	21,40	
108		44.0	25 06	14.8	1.5	19.10.69	24	[6]
111	3104	45.7	22 53	14.7	2.0	1.01.70	21	
118		37.3	24 20	17.5	3.6	6.12.69	21	
119		37.8	23 25	20.0	6.0	9.01.70	40	
139		38.7	23 12	17.8	2.7	23.02.68	40	
157	2144	43.1	23 26	16.4	1.2	19.09.69	40	
					1.6	22.09.69	40	
205		35.7	24 47	19.4	5.0	8.10.70	21,26	[8], 40

2. Repeated Flares of Previously Known Flare Stars. Together with the 44 new flare stars observed at Byurakan, Asiago, and Budapest (Table 1), we also give repeated recordings of flares of previously known stars. Table 2 gives the relevant data with the exception of repeated flares of star No. 18, which is given separately in [9].

From Table 2 and Table 5 of [4] we have constructed a list of all stars for which up to the present time repeated flares have been observed (Table 3). In addition to the number and photographic magnitude, the number of flares observed (k) is given for each star.

Thus, if we ignore the star HII 2411, of the remaining known flare stars repeated flares have been observed for 44 of them; for 28 of them, two flares; for six, three flares; for five stars, four flares; for one star, five flares; for two stars, six flares; for one star, nine flares; and for one, 12 flares.

From the simple equation [1]

$$n_0 = \frac{n_1^2}{2n_2}, \tag{1}$$

derived under the assumption that the probability of recording k flares in a randomly chosen flare star has a Poisson distribution, we find that $n_0 = 474$. From this we obtain a total for the number of flare stars of $N = 681$. Here n_0, n_1, n_2 are the numbers of flare stars for which no flares, one flare, and two flares have been recorded.

3. Representation of the Observations by Two Poisson Distributions. However, a simple Poisson distribution

$$n_k = Ne^{-a}\frac{a^k}{k!} \tag{2}$$

does not represent the values of n_k given in Table 3 satisfactorily for any value of a. But the addition of two Poisson distributions does give adequate representation of the numbers n_k, as we see from Table 4.

TABLE 3. Flare Stars in the Pleiades for Which Repeated Flares Have Been Observed

№	Star (HII)	m_{pg}	k	№	Star (HII)	m_{pg}	k
55	2411	15.5	61	25		15.2	2
18		16.8	12	27		19.0	2
8	357	14.5	9	39		16.7	2
14	906	15.9	6	48	1061	15.1	2
101		17.8	6	51	1827	15.9	2
17	1306	14.6	5	56	2601	16.0	2
21	1653	14.6	4	68	134	15.6	2
62		16.0	4	73	335	14.8	2
102		19.0	4	79		17.2	2
149	146	15.6	4	88	2193	15.1	2
157	2144	16.4	4	90		18.0	2
15	16	18.0	3	92		18.0	2
16	1286	16.4	3	93	2602	16.4	2
36		17.1	3	70	212	15.3	2
40		18.0	3	96		18.4	2
108		15.8	3	99		16.8	2
118		17.5	3	103		16.2	2
2		19.0	2	107	2208	15.3	2
5		18.6	2	111	3104	14.7	2
10		17.5	2	119		20.0	2
19	1531	14.4	2	121		18.1	2
20		20.2	2	139		17.8	2
				207		19.4	2

The last row of Table 4 gives the numbers of flare stars for which more than 6 flares have been observed.

The values of n_k in the third column of Table 4 were computed by adding two Poisson distributions using Eq. (20) of [1]. Of these distributions, the first corresponds to $N_1 = 677$, $\alpha_1 = 0.33$ and the second to $N_2 = 15$, $\alpha_2 = 4.0$. Since $\alpha_1 = \nu_1 t$, $\alpha_2 = \nu_2 t$, we can assert that of the stars for which repeated flares were observed, there is a large group – about 15 – with a frequency of more than 10 times the average flare frequency. Virtually all the stars of this group must have already been observed and included in the list of know flare stars. In making this conclusion we have actually ignored the fact that, for some of the already known flare stars, observatories have revised old plates to detect flares possibly omitted. In addition, the observer automatically remembers some of the previously detected flare stars and in searching for flares more attentively scans their images. These two factors increase the probability of discovering repeated flares by comparison with the probability of detecting the first flare for an as yet unknown flare star. As a result of this, Poisson's equation must be used in an altered form, taking note of this difference in the probabilities. But here we do not take account of the effect of this factor on the results, postponing it to the time when the revision of existing plates is nearly completed. We note only that, by (1), the above phenomena lead to a reduction in the value obtained for n_0. Hence, we can only emphasize again that the true value of n_0 must in general be greater than that computed by our theory, as already confirmed in [1].

4. The Statistics of Flare Stars. From the available data on stars in the Pleiades we can to some extent verify the earlier conclusion that all stars in the Pleiades weaker than $V = 13^m.3$ (or $m_{pg} = 14^m.3$) are flare stars [1, 10]. As an example we take the stars in the list of physical members of the Pleiades [11], for which the photographic magnitudes lie within the limits $14^m.50$ and $16^m.05$. There are 79 such stars. Comparison of this list with the complete list of 207 known flare stars showed that it contains 26 flare stars. It follows at once from this that the group contains 53 stars for which up to the present time no flares have been observed. On the other hand, starting from the values of n_1 and n_2 for stars in that group for which one and two flares have been observed, respectively, we can determine the number n_0 from (1). Since, in this case, $n_1 = 13$ and $n_2 = 8$, we have $n_0 = 11$ approximately, i.e., the true number of members

TABLE 4. Representation of the Observed n_k by Two Poisson Distributions

k	Obs.	Comp.	k	Obs.	Comp.
0	—	485	4	5	3
1	163	163	5	1	2
2	28	29	6	2	2
3	6	6	>6	2	1

for which no flares have been observed is approximately five times larger than the value of n_0 determined from (1). Of course, the numbers n_1 and n_2 which we have used are very small, and so this disagreement can, with some stretch, be attributed to random fluctuations in the values of n_1 and n_2. As a result, it is appropriate to try to derive the value of n_0 starting from all the statistics of flare stars in the group, i.e., to find the values of the two parameters in the Poisson equation which best represent all the observed numbers $n_1, n_2, \ldots, n_k$. But since the numbers $n_3, n_4, \ldots$ are even smaller (than those of n_1, n_2), we seek the values of the parameters N and a in the Poisson equation

$$n_k = Ne^{-a}\frac{a^k}{k!},$$

which give the best representation of the three observed numbers n_1, n_2, and $\sum_{k\geqslant 3} n_k$, which are 11, 8, and 5, respectively.

But first we note that if we take N as the total number of all stars in the group, i.e., we put N = 79, and hence $n_0 = 79 - 26 = 53$, we thereby determine the exact values of the two parameters, i.e., N = 79, and $a = 0.40$. With this assumption we have the theoretical values of n_1, n_2, and $\sum_{k\geqslant 3} n_k$, which are given in the following table together with the observed values:

n_k	Comp.	Obs.
n_0	53	—
n_1	21	13
n_2	4	8
$\sum_{k\geqslant 3} n_k$	0.6	5

It is obvious that the above assumption that N = 79 must be rejected, and we must seek N and a such that, as already mentioned, we can best represent the three numbers. It appears that to do this we have to take N = 37 and $a = 1.2$. For these values of the parameters we have:

n_k	Comp.	Obs.
n_0	11	—
n_1	13	13
n_2	8	8
$\sum_{k\geqslant 3} n_k$	4.4	5

With this representation we obtain $n_0 = 11$, i.e., we have obtained the same value of n_0 which we obtained from (1).

If we accept this result and do not introduce any complicating assumptions, we find that during the time of the observations which we have used, only about half the stars in the selected group of members of the Pleiades flared.

Three possible interpretations of this important conclusion suggest themselves:

1. Not all the stars of the Pleiades fainter than $V = 13^m.3$ are flare stars at this time, but only some of them (about half). Since we have used only the data on bright stars ($m_{pg} \leq 16.0$) in our calculations, i.e., stars which in their present stage of physical evolution (and not according to their calendar age) do not

differ strongly from stars for which flares are not observed, then about half of these have not yet flared. In this case we can assume that if we include weaker stars the proportion of flare stars increases towards 100%.

2. A large number of the flare stars exhibit a cyclic flare activity, with periods of the order of 10 years and more, for more than half the time the activity of the stars is several times less than the "average activity". It is obvious that the periodicity of these changes is not a necessary assumption. We can also assume that these changes are not strictly cyclic.

3. The stars in the group are binaries – the weaker companion, not the principal component, being the flare star. We cannot observe flares for stars whose companions are very faint – more precisely, whose companions are faint even at the most intensive flare.

5. A Hypothesis Concerning the Cyclic Nature of Flare Activity. Of the above three hypotheses it is difficult to choose the correct one because of inadequate actual data. We note, however, that the third hypothesis is somewhat artificial. Moreover, by accepting this hypothesis, we actually incline to the conclusion that the total number of faint stars in the Pleiades is three of four times greater than the initial minimum estimate. As for the other two hypotheses, they require not more than twice the initial estimate. We note that, nevertheless, the possibility of explaining the flares of at least some of the stars as those of their physically or optically near neighbors is not excluded. Hence it is a real problem to check whether all the members of the Pleiades are binaries.

Although we find it difficult to give arguments against the first hypothesis, we note that there are data in favor of the second hypothesis. They are that it is possible to give at least some examples of stars for which observations almost directly indicate variable activity.

Thus, systematic observations of flare stars in the Pleiades were, as is well known, begun by Professor Haro at the Tonantzintla in February 1963, the first flare stars being observed on February 15. These were Nos. 5, 55 (HII 2411), and 14 (HII 906). The flare of star No. 14 was of amplitude $3^m.0$ in the ultraviolet. The following night a second flare of the same star was observed with amplitude $2^m.0$. In the Fall of 1963 two more flares of star No. 14 were observed with amplitudes $1^m.5$ and $1^m.0$. Finally, in 1965 a further flare of amplitude $0^m.8$ was observed. In 1966 and 1967 no flares of this star were observed, but in 1968 at Tonantzintla another flare [12] of amplitude $2^m.2$ was observed. In 1969-1970 no flares were observed. We have the quite definite impression that the star was noticed in February 1963 somewhat near the maximum of its flare activity, which then died down. Indeed, in 1963 the frequency of flares was approximately eight times greater than the average frequency in the following years. If star No. 14 were an unique example, it would be possible to assume that we were dealing with a random fluctuation. But we have other examples. The star No. 157 = HII 2144 was observed as a flare star at Byurakan on a plate on August 19, 1969, and three days later a second flare was observed there. The amplitudes of these flares at photographic lines were $1^m.2$ and $1^m.6$. In the following months of that year two more flares of the star were observed at Tonantzintla [4] with ultraviolet amplitudes of $1^m.2$ and $1^m.0$. It is significant, however, that between 1963 and 1968 no flares of that star were observed. Unfortunately, the problem of whether this star belongs to the physical members of the Pleiades is not clear since there were a large number of errors in measuring μ_δ [11]. The value of μ_α is in agreement with the assumption that the star is a physical member. We note also star No. 108, for which three flares were observed in 1969, before which none were observed [5, 12], and the star No. 101 for which one flare was observed in each of the years 1963 and 1965 and four flares in two months of 1968 [1, 5, 12]. There are several other facts of a detailed nature. All compel us to give preference to the second hypothesis, although the final solution of the problem is only possible on the basis of a stricter analysis of the observed facts. In addition, we do not exclude the possibility that in spite of the validity of the second hypothesis there may be factors underlying one other hypothesis which have an effect on the statistics of flares.

The authors wish to express their deep gratitude to L. Pigatto and L. Rosino for communicating their discoveries of new flare stars before publication, and also to Professor G. Haro for valuable discussions while he was in Byurakan in the Fall of 1970.

Note Added in Proof. After the present article went to press, new flare stars were observed at Byurakan Observatory, as were repeated flares of known flare stars in the Pleiades. The data on these flares are given in the Appendix. E. S. Kazaryan and G. B. Oganyan, to whom the authors express their gratitude, took part in the observations of these stars and also in the observation of several other flare stars included in Tables 1 and 2 of the main text.

APPENDIX

TABLE A1. New Flare Stars and Repeated Flares of Known Flare Stars in the Pleiades*

№	Star (HII)	α (1900)	δ (1900)	m_{pg}	Δm_{pg}	Flare date	Telescope
			New flare stars				
211		$3^h43^m.0$	25°17′	20.0	3.8	15.08.69	40″
212	1029	40.5	24 27	15.2	1.6	8.10.69	21
213		44.5	24 59	17.7	2.4	13.11.69	21
214		44.3	23 55	18.7	4.6	9.12.69	21
215		31.0	25 09	16.7	0.6	9.12.69	21
216		46.3	24 14	18.5	2.3	5.09.70	40
217		39.2	24 11	18.5	2.5	6.09.70	40
218		40.1	24 56	⩾21.0	⩾6.5	9.09.70	40
219		43.3	23 52	17.2	1.6	9.09.70	40
220	1289	41.2	24 00	16.0	2.1	25.10.70	21
221		40.9	25 04	18.3	3.1	28.11.70	21
			Repeated flares				
14	906	3 40.2	24 22	15.9	1.2	9.12.69	21
23		42.4	24 36	19.1	3.9	6.09.70	40
55	2411	43.7	24 01	15.5	0.7	9.01.70	40
					1.5	28.09.68	21
					0.5	11.10.69	21
					1.0	16.10.69	21
					0.7	10.11.69	21
75		33.5	25 10	15.8	2.3	25.10.70	21
103		36.9	23 08	16.2	1.2	18.08.69	40
					0.6	9.01.70	40
116		33.5	25 10	18.7	2.9	25.09.70	21
118		37.3	24 20	17.6	1.3	27.09.68	21
160	347	38.5	24 32	16.6U	1.6 U	12.09.70	40
179		38.5	24 22	18.0	2.5	9.01.70	40
					3.3	9.09.70	40

*The total time for the observations was 11 h on the 40" Schmidt telescope and 84 h on the 21".

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