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# SIMULTANEOUS OPTICAL AND RADIO OBSERVATIONS OF FLARE STARS IN THE PLEIADES

H. M. TOVMASSIAN, G. HARO, J. C. WEBBER, G. W. SWENSON, Jr., K. S. YANG, K. M. YOSS, D. DEMING, R. F. GREEN

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Simultaneous optical (at Tonantzintla, Palomar and Prairie Observatories) and radio (at the Vermilion River and Owens Valley Radio Observatories) observations of the flare stars in the Pleiades cluster were made from 1 to 6 October 1972.

11 optical flare-ups were detected. One large flare-up ($>8^m$ in U) was accompanied by radio flare at 170 MHz. The ratio of optical to radio energy output of this flare is about $6 \cdot 10^3$.

I. *Introduction.* To study the behaviour of flare stars at radio wavelengths a few flare stars of UV Ceti type in the solar neighbourhood have been monitored for several hundred hours [1—7]. Only a few radio flares have been recorded, since a flare event does not occur often. More promising are observations of groups or clusters of flare stars, in which the probability of detection of a flare is much higher for the large number of flare stars in the group. Observations of the Orion nebula region rich with flare stars, have been conducted by Slee and Higgins [8]. In spite of a large dilution factor ($\sim$1000) in intensity in comparison with flare stars in the solar neighbourhood, the observations made during only 34 hours resulted in the detection of 9 bright flares. Seven of the optical flares appeared to be accompanied by detectable radio emission at 136/150 MHz.

The Pleiades cluster represents another good location to look for radio emission from flare stars. As it is shown by Ambartsumian et al. [9] the number of flare stars in the Pleiades must be about 1000, and more than 400 of which have been detected up to March,

1974. Moreover, the distance of the Pleiades, equal to 126 *pc*, is more than threefold less than the distance of the Orion nebula ($\sim$400 *pc*). Thus the probability of detection of both optical and radio flares in the Pleiades is very high.

In the present paper the results of an experiment which attempted to detect the radio emission of the flare stars in the Pleiades are given. Simultaneous optical and radio observations were made from 1 to 6 October, 1972, at the following observatories:

1. Tonantzintla Observatory, Mexico,
2. Hale Observatories, California,
3. Prairie Observatory, Illinois,
4. Vermilion River Radio Observatory, Illinois,
5. Owens Valley Radio Observatory, California.

II. *Optical observations*. 1. *Observations at Tonantzintla Observatory*. Observations were made as part of a regular search of the Pleiades region carried out at Tonantzintla with the 24″ Schmidt telescope. During the six first days of October 1972, 22 ultraviolet multiple exposure plates centered in Alcyone were obtained. The number of different exposures was 122 and the total time of effective observations, $25^h10^m$. In some of the plates 6 successive exposures of 10 minutes each were made, with a time interval between exposures of less than one second. In some cases 8 exposures of 10 minutes each were made and in the remainder, 6 exposures of 15 minutes each. On the average, the limiting U magnitude of this material is $17^m_.0$. Table 1 contains the information of the dates (UT). the total times of observations spent each day and

*Table 1*

PHOTOGRAPHIC OBSERVATIONS AT TONANTZINTLA

| Data (1972) | Times (UT) | Number of detected flare-ups |
|---|---|---|
| 1 Oct. | $6^h03^m$—$8^h12^m$ | 1 |
| 2 Oct. | 5 56 — 9 16 | 2 |
| 3 Oct. | 5 50 —10 42 | 2 |
| 4 Oct. | 5 01 —11 00 | 1 |
| 5 Oct. | 5 29 —11 05 | 0 |
| 6 Oct. | 5 43 —11 11 | 3 |

the numbers of flare-ups detected in a given day. The flare-ups detected at Tonantzintla are listed in Table 2; the first column gives the original number assigned to the flare star; A-means Asiago and T-To-

*Table 2*

OPTICAL FLARE-UPS DETECTED AT TONANTZINTLA

| Original No. Flare Stars | Star | R. A. (1900) | Dec. (1900) | Mag. in U (Minimum) | Mag. in U (Maximum) | Date (UT) | Time at Maximum | Notes |
|---|---|---|---|---|---|---|---|---|
| A 66 | — | $3^h43^m.4$ | +23°21′ | 20: | 14.2 | 1 Oct. | $7^h17^m$ | 1—2 |
| T 35b | — | 3 34.1 | 24 28 | 19.8 | 15.8 | 2 Oct. | 6 21 | 2 |
| T 53b | — | 3 44.1 | 24 18 | 22: | 13.5 | 2 Oct. | 8 26 | 2—3 |
| T 18 | — | 3 41.5 | 22 02 | 18.2 | 16.6 | 3 Oct. | 7 36 | — |
| T 75 | — | 3 38.9 | 25 02 | 16.3 | 14.3 | 3 Oct. | 9 34 | 2 |
| T 40b | — | 3 38.1 | 25 21 | 14.8 | 12.0 | 4 Oct. | 6 18 | 2—4 |
| T 39b | — | 3 37.6 | 25 17 | 19.0 | 16.0 | 6 Oct. | 6 38 | 2 |
| T 55 | HII 2411 | 3 43.7 | 24 01 | 16.8 | 16.3 | 6 Oct. | 8 28 | 5 |
| T 160 | HII 347 | 3 38.5 | +24 32 | 16.6 | 15.9 | 6 Oct. | 8 58 | 2—6 |

Notes to Table 2:

1) In the case of flare star A 66 in the first exposure of the plate taken from $7^h12^m$ to $7^h22^m$ the outburst reaches the maximum, mag. U is equal to 14.2. In the second exposure, from $7^h22^m$ to $7^h32^m$, mag. U is equal to 14.9. In the third exposure, from $7^h32^m$ to $7^h42^m$, mag. U is equal to 16.2. In the fourth exposure from $7^h42^m$ to $7^h52^m$, mag. U is equal to 16.8. In the fifth and sixth exposures of this plate the star is not visible. In the preceding plate, in the last exposure which ended at $7^h03^m$ the star was not visible.

2) The photographic reproduction of the flare-up has been published by Haro et al. [10].

3) In the case of flare star T 53b in the first exposure of the plate taken from $3^h16^m$ to $8^h26^m$. mag. U is equal to 13.7. In the second exposure, from $8^h26^m$ to $8^h36^m$, mag. U is equal to 13.5. In the third exposure, from $8^h36^m$ to $8^h46^m$, mag. U is equal to 16.0. In the fourth exposure, from $8^h46^m$ to $8^h56^m$, mag. U is equal to 16.8. In the fifth and sixth exposures of the plate, the star is not visible. In the preceding plate the last exposure which ended at $8^h10^m$ the star was not visible. In the blue and red Mt. Palomar glass copy plates the star does not appear. We suppose that the peak of the outburst took place at $8^h26^m$.

4) The maximum of the outburst of flare star T 40b is reached in the first exposure of the plate taken from $6^h11^m$ to $6^h26^m$, mag. U is equal to 12.0. After the first exposure the brightness decreases monotonically and is still brighter than at normal minimum during the last exposure that ends at $7^h41^m$. This is one of the brigh-test flare star found in the Pleiades region.

5) Flare star T 55 (HII 2411), a Hyades member, flare-up in the eighth and last exposure of a plate taken from $8^h23^m$ to $8^h33^m$. In the following plate, in which the first exposure was taken 7 minutes later, the star appears at normal minimum.

6) Flare star T 160 (HII 347) in the first exposure of the plate taken from $8^h43^m$ to $8^h53^m$ appears at normal minimum. In the second exposure from $8^h53^m$ to $9^h03^m$, mag. U is equal to 15.9. In the third exposure taken from $9^h03^m$ to $9^h13^m$, mag. U is equal to 16.2. In the fourth exposure taken from $9^h13^m$ to $9^h23^m$, mag U is equal to 16.4. From exposure five through eight — $9^h23^m$ to $10^m03^m$ — the star goes back to minimum.

nantzintla. Of the 9 flare stars listed, 5 were already known flare stars in which the outbursts repeated, the other 4 (indicated by letter b) were „new“ flare stars. The coordinates and magnitudes in U during minimum are just approximate. The magnitude U at maximum was derived using as standards the U magnitudes from Johnson and Mitchell [11], the time at maximum corresponds either to the mid-point of the exposure when the star reaches its maximum or to the time obtained from the derived light curve.

2. *Observations at Palomar*. Observations were made with Palomar 18″ Shmidt. While Moon was down, Kodak Commercial film, baked 24 hours at 63°C, was used with a Schott GG13 filter. This film has the spectral response of an O emulsion and yields a standard B magnitude. Four 15-minute exposures were taken on each film, with a limit of 17-th magnitude per exposure. With the Moon up, an amber Kodak Wratten 106 filter in combination with GAF 2863 film, a panchromatic emulsion with spectral sensitivity that cuts off just before $H_\alpha$ was applied. It gives an approximate V magnitude with maximum response at about 5500A. Again, four exposures were taken on each film, with exposure times of 3 to 5 minutes each, depending on the brightness of the Moon.

Magnitudes were determined with an iris photometer on the bases of photographic measurements by Johnson and Mitchell [11]. Pre-flare magnitudes were estimated by Charles Kowal from the Palomar Sky Survey prints. Positions were obtained with a Grant measuring engine on the bases of 1900 coordinates given by Hertzsprung [12]. The total times of observations and the number of flare-ups detected at Palomar are given in Table 3. In Table 4 the information on the detected flare-ups is given. The large flare-up observed in B was detected also in Tonantzintla in U. The finding charts for the flares detected only at Palomar are presented in Fig. 1.

*Table 3*

PHOTOGRAPHIC OBSERVATIONS AT PALOMAR

| Date (1972) | Times (UT) | Number of detected flare-ups |
|---|---|---|
| 1 Oct. | $10^h28^m$—$11^h20^m$ | 1 |
| 2 Oct. | 06 23 —11 20 | 1 |
| 3 Oct. | 05 58 —11 18 | — |
| 4 Oct. | 05 52 —09 52 | 1 |

*Table 4*

OPTICAL FLARE-UPS DETECTED AT PALOMAR

| Original No. Flare Stars | Star | R. A. (1900) | Dec. (1900) | Mag. in Minimum | Date (UT) | Mag. in Maximum | Time at Maximum |
|---|---|---|---|---|---|---|---|
| P 1 | — | $3^h42^m20^s$ | +25°52.3 | 15.3(V) | 1 Oct. | 14.8 (V) | $11^h10^m$ |
| P 2, T 53b | — | 3 44 03 | 24 18.5 | >21 (B) | 2 Oct. | 15.5 (B) | 08 21 |
| P 3 | HII 2940 | 3 45 09.1 | 24 10.75 | 16.65 (B) | 4 Oct. | 16.15(B) | 07 36 |

3. *Observations at Prairie Observatory.* The 102-*cm* reflector at Prairie Observatory was used for direct photography at f/8 focal ratio; the resulting field was $0.9 \times 1.2$ degrees, thus covering the central region of the cluster. Exposures were 10 minutes each on unfiltered Ia-O emulsion; they were limited by cluster nebulosities rather than moonlight. The limiting magnitude was $17^m$, and no flares with $m \geqslant 0.3$ magnitude were observed.

III. *Radio observations.* 1) *Observations at the Vermilion River Observatory.* Observations were made at a frequency of 170 MHz with the 37-meter radio telescope of the University of Illinois. A receiver on loan from the NRAO had a system noise of 1200°K. An IF bandwidth of 2 MHz was employed to reduce contributions from man-made interference at low frequencies which was frequently severe at the site of the radio telescope. During observations reported here the interference was relatively less. Two helical feeds were employed: one on-axis the width of which at half-power points is equal to 4.5°, and pointed towards the Alcyone covers the whole region of the Pleiades, and one providing a comparison beam eight degrees south of the main beam. A three-port Dicke switch was used, which switched between main beam, comparison beam and a resistive load at ambient temperature. Two programmable phase detectors provided outputs representing main beam minus load and comparison beam minus load. The comparison of records of both outputs permitted distinguishing the external interference and gain fluctuations of the receiving system from the expected radio flares of flare stars. A noise generator was used to inject a 40°K calibration signal. The phase detectors were balanced by a programmable gain modulator which acted only upon the resistive-load segment of the IF signal.

Calibration of the sensitivity of the overall system was done by taking declination scans of Cygnus A and Taurus A, whose flux densities were assumed to be 8700 and 1500 f.u. respectively (1 f.u. = $=10^{-26}$ W $m^{-2}$ $Hz^{-1}$). The average measured sensitivity was $12.6\pm2$f.u./°K, corresponding to a system overall efficiency of 21 percent.

In total, only 8 hours 40 minutes of relatively interference-free observations were made during the observing period from 1 to 6 October, 1972. Observations obtained from $07^h15^m$ to $08^h20^m$ and from $09^h20^m$ to $09^h40^m$ on the 1 October (in UT), from $07^h30^m$ to $10^h20^m$ on the 2 October, from $07^h45^m$ to $08^h30^m$ on 3 October, from $09^h00^m$ to $09^h20^m$ and from $09^h30^m$ to $10^h10^m$ on the 5 October, and from $06^h08$ to $06^h50^m$ and from $08^h00^m$ to $10^h00^m$ on the 6 October are relatively free from interference which makes only about $7^h40^m$ of useful observations made simultaneously with optical observations.

2. *Observations at Owens Valley Radio Observatory.* The 40 meter telescope at OVRO was used for observations at 327 MHz. A total power system was employed on 1 and 2 October, and a switched radiometer on 3 to 6 October. Observations were severely hampered by electrical storms and by airborne communications. Only a few hours of satisfactory data were obtained, mostly on 5 and 6 October. Baseline drift and the lack of an off-source comparison beam made it impossible to determine if any radio flare were detected.

IV. *Results and discussion.* Due to bad weather at Tonantzintla, Palomar and Prairie Observatories, and heavy interference at the Vermilion River and Owens Valley Radio Observatories, the total duration of simultaneous optical and radio observations of the Pleiades is less than 8 hours.

The inspection of radio records obtained at the VRO revealed a radio event associated by a large optical flare (T53b) on 2 October, observed at Tonantzintla and Palomar. Although the radio record is not free from interference, the presence of a radio flare seems to be definite. The star which flared is very weak — it is fainter than $22^m$ in U and fainter than $21^m$ in B — and thus is a dwarf of late M type with absolute magnitude equal to or greater than $V=15.0$, if it is a member of the Pleiades. As it is shown by Haro [13] at least 25 % of 437 flare stars, discovered up to March 1974 in an area of about 20 square degrees centerd in Alcyone may not belong to the Pleiades cluster. Therefore it is difficult to say with certainty if the detected flare stars without known proper motions are members or non-members of the Pleiades group. They can be members of the Hyades, members of UMa stream which are widely dispersed over the sky or members of some other groups of stars or just field stars. It may be a relatively nearby star similar to van Biesbrock's star on which Herbig [14] found a flare-up. Radio and light curves of this flare-up are shown in Fig. 2.

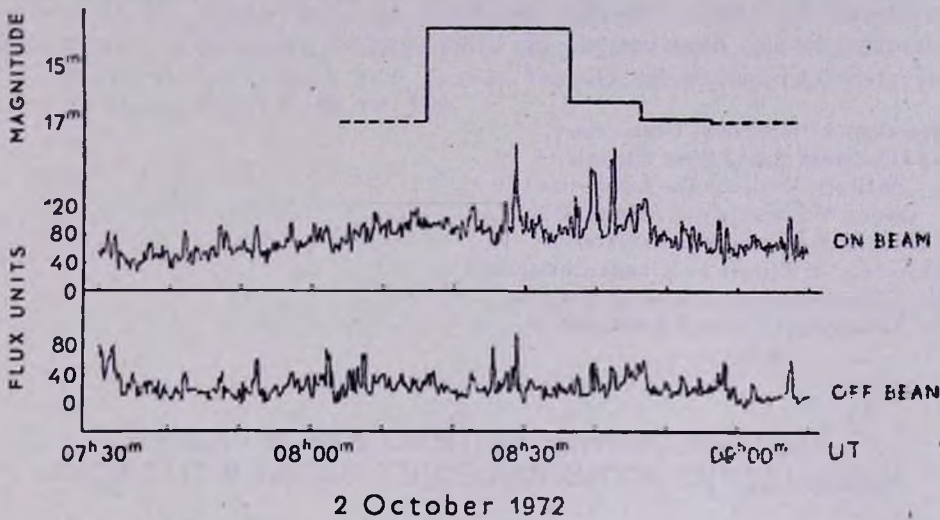


Fig. 2. The light (in U) and radio (at 170 MHz) curves of the flare occured on 2 October, 1972.

The radio curve was plotted by reading off the positions of the recorder pen above an arbitrary zero level at intervals of 12 *sec*. The comparison beam minus load output is also presented in the same way in Fig. 2. The optical and radio flares started and finished almost simultaneously, the radio one being just slightly longer. The peak radio flux density of this flare is about 35 f.u. (corrected for being at the distance of 22 *arc min* from the beam center). The energy emitted at radio wavelengths is about $4 \cdot 10^{26}$ J, assuming that the spectral index of the flare is equal to —1.65 [8] and that the star radiates uniformly through $4\pi$ steradians. It was also assumed that the star is a member of the Pleiades the distance of which is 126 *pc*. The optical energy of the flare was calculated assuming that a star with radius of 0.1 $R_{\odot}$ radiates as a black-body with a temperature of about 3000°K and flares uniformly into $4\pi$ steradians. The excess flare power Be, of the order of $2.5 \cdot 10^{29}$ J, was obtained from the relationship $I_{Be} = I_{B0} (10^{-0.4 \Delta m_B} - 1)$.

Thus the ratio of optical to radio energy output of the flare is about $6 \cdot 10^{3}$, which is of the order of that found by other observers for UV Ceti type flare stars and flare stars in the Orion stellar association. Obtained ratio of optical to radio energy output of the flare will not change appreciably if the star is not a member of the Pleiades cluster.

Only the upper limits of radio flares, equal to about 30 f.u. could be stated for three flare-ups observed at Tonantzintla on the 6-th October. Radio observations of other optical flares are very much affected by interference.

Byurakan Astrophysical Observatory,
NRAO, Green Bank, West Virginia,
Instituto Nacional De Astrofisica
Optica Y Electronica, Tonantzintla,
University of Illinois Observatory,
University of Illinois at Urbana-Champaign,
Hale Observatories, California Institute
of Technology, Carnege Institution of
Washington.

## ОДНОВРЕМЕННЫЕ ОПТИЧЕСКИЕ И РАДИО-НАБЛЮДЕНИЯ ВСПЫХИВАЮЩИХ ЗВЕЗД В ПЛЕЯДАХ

Г. М. ТОВМАСЯН, Г. АРО, ДЖ. С. ВЕББЕР, Г. В. СВЕНСОН,
К. С. ЯНГ, К. М. ЙОСС, Д. ДЕМИНГ, Р. Ф. ГРИН

Представлены результаты одновременных оптических (в обсерваториях Тонанцинтла, Паломарской и Прерии) и радио (в радиоастрономических обсерваториях Вермилион Ривер и Оуэнс Велли) наблюдений вспыхивающих звезд в Плеядах, выполненных с 1 по 6 октября 1972 г.

Обнаружено 11 оптических вспышек. Одна вспышка ($>8^m$ в U) была сопровождена радиовспышкой, зарегистрированной на частоте 170 *Мгц*. Отношение энергий этой вспышки в оптическом и радиодиапазонах равно около $6 \cdot 10^{3}$.

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