

Determination of the correlation coefficient of selected short-periodic comets of the Jupiter family and solar activity

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The paper presents the study of the dependence between photometric parameters of selected short-period comets of the Jupiter family and the activity of the Sun. As a quantity of solar activity, we used the sunspot area, the Wolf number, the annual mean solar radio flux, the solar flare index (full disk), and the annual mean *AA*-index solar activity. To study the correlation between cometary and solar activity the Dobrovolsky method was used. It has been found no direct correlation between the absolute stellar magnitude and the photometric parameter of comets with individual parameters of solar activity. Moreover, the correlation coefficients show that some comets are not associated with solar activity.

Key words: comets: individual; Sun: activity, sunspots, flares

INTRODUCTION

The investigation of short-period comets is carried out by studying the evolution of their brightness in each appearance. The study of the same comet in a certain appearance allows us to reveal different mechanisms of nucleus activity as it was done in [1, 4–7, 9–13, 21, 23]. To study the dependence between the brightness of comets and solar activity, as well as for many photometric studies, the total brightness of the studied comet should be known with the greatest possible degree of accuracy. The dependence of the annual number of comets on the level of solar activity has been studied in [1, 7, 8, 28].

For instance, in [21, 22] the absolute magnitude of comet 2P was examined in 12 appearances making the conclusion that the appearance of comet 2P in 1901, 1905, 1924 and 1934 have a direct relation with the Wolf numbers. The similar result was found for the comet 21P which absolute brightness also shows the dependence on the level of solar activity (i.e. the Wolf number).

The method of qualitative comparison of features is convenient for the study of the cometary phenomena, which was firstly used in [7]. The essence of the method is to divide the entire observation period T of the comet into n equal time intervals τ so that each of them has no more than one maximum of the Sun's activity or the brightness of the comet m . For our case, we chose one orbital period of the

comet around the Sun P and the values of the absolute stellar magnitude and photometric parameter of comets. Most comets of the Jupiter family have an orbital period around the Sun from 3.3 and 20 years. Therefore, one solar cycle (i.e. 11-year solar cycle) was taken as a unit of the activity of the Sun.

The study of parameters of solar and cometary activity plays a key role in the establishing of the connection between these phenomena. In this work we determine the correlation coefficient of 16 most active comets of the Jupiter family from the activity of the Sun. Numerous studies have already studies the relation between the photometric parameters of these comets with the activity of the Sun [1, 4–6, 8–13, 21–23], but we expand this analysis using observations of recent years (from 1990 to 2022).

METHOD AND RESULT

The existence of active processes in the nuclei of short-period comets during the 11-year cycle with solar activity was expressed in numerous studies [7, 8]. These studies showed the presence of a two-peak shape distribution of the total number of comets and the number of the brightest comets during the 11-year solar cycle.

In this work, we have chosen the absolute magnitude in one orbital period of short-period comets 2P/Encke, 6P/d'Arrest, 7P/Pons-Winnecke, 9P/Tempel 1, 10P/Tempel 2,

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17P/Holmes, 19P/Borrelly, 21P/Giakobini-Zinner, 26P/Grigg-Skjellerup, 41P/Tuttle-Giakobini-Kresak, 45P/Honda-Mrkos-Pajdusakova, 46P/Wirtanena, 51P/Harrington, 67P/Churyumov-Gerasimenko, 73P/Schwassmann-Wachmann 3 and 81P/Wild 2.

For this, graphs of the absolute stellar magnitude and photometric parameter of the comets. In addition, for each appearance of comets, we analysed the dependence between the absolute stellar magnitude and the activity of the Sun. As an indicator of solar activity in the sunspot area we use the well-known Wolf number, the annual mean solar radio flux, the solar flare index (full disk) and the annual mean AA-index solar activity from [3].

This way allows you to identify a specific event using the relationship between the absolute stellar magnitude and the photometric parameter from the activity of the Sun. To determine the correlation coefficient between the photometric parameter and the absolute magnitude with the activity of the Sun accurately, we followed the approach from [7]:

$$r = \frac{N_{mW}N - N_WN_m}{\sqrt{\bar{N}_W\bar{N}_{\bar{W}}\bar{N}_m\bar{N}_{\bar{m}}}},$$

where N_{mW} is the number of intervals with maxima W and m , N_W is the number of intervals with maxima W , but no maximum m , N is the number of intervals without maxima m , N_m is the number of intervals without a maximum W , but with a maximum m , $\bar{N}_W$ is the total number intervals with maxima W , $\bar{N}_{\bar{W}}$ is the number of intervals without maxima W , $\bar{N}_m$ is the number of intervals without maxima m . Where the standard deviation of this correlation coefficient is determined based on the total number of intervals n as:

$$\sigma = \frac{1 - r^2}{\sqrt{n}},$$

The obtained correlation coefficients are presented in Table 1 for all studied comets. Analysing the correlation between the absolute magnitude of the 2P comet and the activity of the Sun coefficients vary from 1.05 to 0.33. For instance, the correlation with the sunspots area shows a positive trend with coefficient 1.05, with the Wolf number ($r = 0.88$), with the AA index ($r = 0.86$). At the same time, we obtained weak correlation with the flux of radio emission at a wavelength of 10.7 cm the value ($r = 0.33$) and the flare index of solar activity from the full disk of the Sun ($r = 0.43$). The correlation coefficients for the photometric parameter and the solar activity also lie in the range of 1.24 to 0.33. We obtained the positive correlations with coefficients $r = 1.24$ for S , $r = 1.15$ for W , $r = 0.76$ for AA , but weak correlations for $F_{10.7}$ and FI ($r = 0.59$ and 0.33 , respectively). Although dependencies with the Wolf number and the sunspot area have been found, there is no direct relation for other types of solar activity.

In the case of comet 6P, the correlation coefficients show quite different trend, because for the sunspot area and the solar FI index the values of the correlation coefficient with the absolute magnitude are $r = 1.12$ and $r = 1.00$, and for the Wolf number the value is also close to unity $r = 0.90$. On contrary, there is no correlation with the AA index ($r = 0.14$) and $F_{10.7}$ ($r = 0.00$). The values of the correlation coefficient for the dependence between photometric parameter and the Wolf number or the sunspot area are close to unity ($r = 0.94$ and 0.95). For other parameters, the correlation values show weak correlations (from 0.58 to 0.25) and therefore, we can't conclude the presence of direct relation between photometric parameters and solar activity.

For comet 7P, the photometric parameter shows positive correlation only with S and W ($r = 1.05$ and 1.06 , respectively). For other solar activity parameters, the values of correlation coefficient show weak correlations, e.g. $r = 0.27$ with $F_{10.7}$, $r = 0.12$ with AA index, and no correlation with FI index. At the same time, the correlation between the absolute magnitude and all activity parameters is weak, and correlation coefficients lie in the range from 0.89 to 0.41.

The values of the correlation coefficient for the absolute magnitude of the comet 9D revealed the correlation only with S ($r = 1.10$) and FI index ($r = 1.17$). Other coefficients show weak correlations, e.g. $r = 0.89$ for W , 0.27 and 0.25 for AA and $F_{10.7}$ indices, respectively. On the contrary, the photometric parameter does not show strong correlation with any activity of the Sun.

According to the values of the correlation coefficient for comet 10P, the absolute magnitude correlates only with S and $F_{10.7}$ ($r = 1.07$ and 1.06). Other types of solar activity gave the values $r = 0.74$ and 0.91 for W and AA index, and no correlation with the FI index. The values of the correlation coefficient from the photometric parameter for all types of solar activity are intermediate and lie within 0.86–0.17.

The absolute magnitude of comet 17P shows strong correlation with the FI index ($r = 1.02$) and $F_{10.7}$ ($r = 1.00$). Similar trend was found for the photometric parameter and $F_{10.7}$ ($r = 1.06$). The values of the correlation coefficient for other types of activity, both for the absolute magnitude and for the photometric parameter, are showing weak correlations. At the same time, the photometric parameter shows no correlation with FI and AA indices for this comet.

It was found that the photometric parameter and the absolute magnitude of the comet 19P correlate with the sunspot area and the Wolf number, and there is no correlation between the absolute magnitude and the flare index. For the remaining indicators of solar activity the photometric parameter and absolute magnitude of this comet show weak correlations (see Table 1).

For comet 21P, the values of correlation coefficient for the absolute stellar magnitude and all types of solar activity are intermediate and lie in the range from 0.76 to 0.20. While the photometric parameter correlates only with the solar area and shows no correlation with FI index. For the remaining types of activity the studied correlations are weak.

Similarly to the case of comet 19P, the photometric parameter of comet 26P show strong correlation with the Wolf number and the sunspot area. In addition, the absolute magnitude of this comet shows correlation with the sunspot area. It was revealed that the $F_{10.7}$ and AA indices do not correlate with the absolute stellar magnitude. Also, no correlation was found between the photometric parameter and AA index. For other types of solar activity, correlation coefficient values are intermediate.

The absolute stellar magnitudes of comets 41P, 45P, 67P correlate with the area of sunspots, and in the case only of comet 67P it correlates with the Wolf number and FI index.

The absolute magnitude of comet 51P shows correlation only with $F_{10.7}$ index, while photometric parameter seems to correlate also with W . For comets 46P, 73P and 81P, the absolute magnitude values have no correlation with the FI , $F_{10.7}$ and AA indices. At the same time, the photometric parameter for comet 81P does not correlate with FI and AA indices.

DISCUSSIONS AND CONCLUSIONS

The value of the correlation coefficient r is a numerical measure, where $r = 1$ indicates to the presence of a strong correlation (i.e. events appear together or one event causes another). In this case, the light curves of comets and solar activity should be smoothed out. The case of $r = 0$ is absence of the correlation between parameters (i.e. no connection between events). If the value of the correlation coefficient is negative ($r = -1$), the appearance of one event excludes the appearance of another (i.e. presence of a certain feedback).

Analyzing results shown in Table 1, we can conclude that there is clear correlation between selected solar activity parameters and absolute stellar magnitude, as well as with the photometric parameter of studied comets.

Previous studies of comet 2P/Encke [24, 25] found that its absolute magnitude maxima coincide with the Wolf number maxima in 1835, 1848, 1870, 1934, 1941, 1967, 1990, and 2000, similarly as the minimum of its absolute magnitude minimum coincide with the Wolf number minimum in 1832, 1842, 1871, 1881 and 1937. For comet 7P/Pons-Winnecke, the absolute magnitude maxima coincide with the Wolf number maximum only in 1915, 1970, 1989, and 2002, and the minima of the absolute magnitude with the minimum of the Wolf number coincide in 1921, 1945, 1975 and 1995. Moreover, for both comets, it

has been observed the shifts of the absolute magnitude maxima and minima with respect to the maxima and minima of the Wolf numbers. For comet 9P, the absolute magnitude maximum coincides with the Wolf number maximum in 1967, 1978, 1989, and 2011, and the minimum coincides in 1972 and 1983. The maximum of the photometric parameter coincides with the in 1867 and 1967, while the minimum coincides in 1879, 1978, 1989, and 2000. For comet 10P, the values of the maximum absolute magnitude coincide with the maximum Wolf number in 1873, 1894, 1904, 1920, 1946, and 1986, and the minimum coincides in 1899, and 1999. Although shifts are observed in most maxima (a decrease in absolute magnitude and an increase in the value of the Wolf number, or vice versa). The photometric parameter is also showing the same trend.

For comet 17P, the maximum magnitude coincides with the maximum Wolf number only in 1972 and 1993, while the minimum coincides in 1979 and 2007. The comet 19P/Borrelly, the maximum magnitude, and maximum Wolf number coincide in 1967 and 1981, and the minimum coincides in 1953, 1974, and 2008. In some maximum and minimum, we are able to detect small shifts of points. In addition, we observed several antiphase trends (e.g. maximum of solar activity with a minimum of cometary activity, or vice versa) in 1932, 1994, and 2014 for magnitude and in 1911, 1953, 1987, and 2014 for the photometric parameters. At the same time, the minima coincide in 1932, 1974, 1994 and 2008. The absolute magnitude of comet 21P shows slightly different behavior with respect to other comets, in 1940 the value of the magnitude constantly increases during the next three occurrences and does not show any dependence on the maxima of solar activity. A similar trend was detected for the photometric parameter, the maximum time covered five occurrences and five solar cycles at once. Two maxima and one minimum with a shift were observed, there is also two antiphase with point shifts.

The evolution of the photometric parameter and the absolute stellar magnitude of the comet 41P fluctuates with the activity of the Sun only after 1960. The absolute magnitude is directly related to the activity of the Sun at the appearances in 1995 and 2000. For the photometric parameter, the dependence begins in 1962, then in 1978, and in other cases, simultaneous increases in brightness with decreases in solar activity are observed, or vice versa. The maximum absolute magnitude of comet 81 does not coincide with solar activity, the minima coincide only in two cases, 1984 and 2016. In four cases, an inverse correlation is observed, i.e. at the maximum absolute magnitude, solar activity minima are observed (in 1978, 1997, and 2010) and vice versa in 2003.

According to the current paradigm the nuclear activity of the comets is associated with solar activity, but the obtained results presented in Table 1 shows

that activity of comets 21P, 46P, 73P, 67P and 81P does not correlate with solar activity. In most cases, the dependence was revealed only between the absolute magnitude of the comet (e.g. 2P, 6P, 9P, 10P, 17P, 26P) and sunspot area, Wolf number, F10.7, and AA indices, while the photometric parameter of comets usually correlates only with the area of sunspots and the Wolf number.

In [1, 8, 21–23, 28] was suggested that the decrease of the absolute magnitude for these comets can be caused by the present of a refractory crust. In [20] space observations confirmed that some cometary nuclei show signs of partial coverage by a refractory crust. In addition, some of these comets are considered active ones [14–17, 26], because the flare activity of comets located in the plane of the ecliptic can be caused by a collision with meteoroid swarms. This phenomenon may be the reason in the cases where our analysis does not reveal the strong dependence between some comets' activity and solar activity. This scenario agrees with the study of the probability of the cometary collision with a specific meteoroid shower in the case of comets 2P (in the appearances of 1924, 1937, 1941, 1947, 1951), 6P (in the appearances of 1950 and 1976), 7P (in the appearance of 1933), 10P (in the appearance of 1930), 19P (in the occurrences of 1918, 1994, 2011), 26P (in the occurrence of 1927) and 81P (in the occurrence of 1997) [27].

In [2] the variation of the brightness and outburst of comets is explained by the influence of high-velocity flares with a speed of 500–750 km/s. At the same time, in [18] it has been found the correlation between the brightness of comet C/1995 O1 and geomagnetic activity C_9 and C_p indices.

However, it should be noted that a detailed study of the comet light curve in one appearance usually allows for identifying some connection with specific indicators of solar activity. For instance, such correlations have been found for several short-period and long-period comets in [2, 4–7, 9–13, 18, 22, 23, 28].

According to [7], the value of r can be considered statistically significant if the absolute value of r is three times the standard σ . So intermediate values can be associated with active processes taking place in the nuclei of studied comets. In the case of all comets discussed above, during their repeated return to the Sun the active processes in the form of destruction of the nucleus, the formation of anomalous tail and gas and dust jets, especially the ejection from local parts of the surface of the nucleus, which were repeatedly observed using spacecraft [15–17, 20, 26, 27]. However, the direct correlation between the activity of comets and solar activity may be revealed only based on the detailed study of each individual comet in a single appearance, especially analysing the change of comet brightness before and after the perihelion of the orbit.

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Table 1: The correlation coefficient r and its standard deviation σ for the selected comets of the Jupiter family and different type of solar activity (the sunspot area S , the Wolf numbers W , the flare index FI , AA -index and the absolute value of the radio emission flux with a wavelength of 10.7 cm, $F_{10.7}$).

Comets	Absolute magnitude of comets										Photometric parameters of comets									
	S		W		FI		AA index		$F_{10.7}$		S		W		FI		AA index		$F_{10.7}$	
	r	σ	r	σ	r	σ	r	σ	r	σ	r	σ	r	σ	r	σ	r	σ	r	σ
2P	1.05	0.01	0.88	0.03	0.43	0.23	0.86	0.05	0.33	0.18	1.24	0.06	1.15	0.04	0.33	0.25	0.76	0.08	0.59	0.13
6P	1.12	0.05	0.90	0.04	1.00	0.00	0.14	0.30	0.00	0.00	0.95	0.02	0.94	0.02	0.58	0.25	0.52	0.22	0.25	0.29
7P	0.84	0.06	0.87	0.05	0.41	0.31	0.48	0.20	0.89	0.006	1.05	0.02	1.06	0.02	0.00	0.00	0.12	0.30	0.27	0.29
9P	1.10	0.05	0.89	0.05	1.17	0.13	0.27	0.29	0.25	0.26	0.88	0.06	0.64	0.16	0.83	0.11	0.16	0.29	0.27	0.29
10P	1.07	0.03	0.91	0.03	0.60	0.22	0.51	0.19	1.06	0.03	0.70	0.10	0.86	0.05	0.61	0.22	0.40	0.22	0.60	0.17
17P	0.94	0.03	0.89	0.06	1.02	0.01	0.74	0.10	1.00	0.00	0.76	0.12	0.72	0.14	0.20	0.09	0.18	0.32	1.06	0.03
19P	1.00	0.01	0.74	0.01	0.00	0.00	0.91	0.05	0.43	0.25	0.75	0.11	1.12	0.06	0.16	0.09	0.61	0.15	0.43	0.25
21P	0.76	0.10	0.58	0.01	0.41	0.34	0.20	0.25	0.60	0.10	1.06	0.03	0.65	0.14	0.00	0.00	0.31	0.28	0.72	0.14
26P	1.29	0.14	0.94	0.02	0.00	0.00	0.23	0.24	0.00	0.00	1.20	0.09	1.07	0.03	0.00	0.00	0.26	0.17	0.25	0.29
41P	1.20	0.12	1.00	0.02	0.20	0.39	0.41	0.26	0.57	0.21	0.80	0.10	0.97	0.01	0.00	0.00	0.41	0.26	0.55	0.21
45P	1.08	0.04	0.80	0.10	0.30	0.03	0.43	0.22	0.38	0.23	0.93	0.03	0.92	0.04	0.54	0.26	0.56	0.18	0.30	0.25
46P	0.80	0.09	0.83	0.08	0.00	0.00	0.25	0.25	0.68	0.14	0.76	0.11	0.62	0.17	0.19	0.02	0.73	0.01	0.47	0.21
51P	0.57	0.23	0.52	0.26	0.18	0.13	0.75	0.01	1.15	0.11	0.91	0.06	1.04	0.02	0.81	0.13	0.90	0.06	1.33	0.26
67P	1.29	0.23	0.89	0.07	1.00	0.00	0.81	0.01	0.43	0.25	0.86	0.09	0.72	0.17	0.86	0.09	0.82	0.01	0.57	0.21
73P	0.57	0.25	0.70	0.17	0.30	0.37	0.00	0.00	0.16	0.25	0.75	0.16	0.91	0.06	0.27	0.37	0.17	0.36	0.16	0.25
81P	0.58	0.25	0.83	0.11	0.27	0.03	0.00	0.00	0.30	0.03	0.65	0.08	0.72	0.02	0.00	0.00	0.00	0.00	0.70	0.18