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Exotic red flares on stars as the observational manifestation of the asteroids in exoplanet systems

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Abstract. The published data on exotic red flares (RFs) obtained using optical/IR photometry was for the first time gathered and discussed in this paper. To date, the RFs have been observed: (a) in IR space missions (1–2 yr long IR brightening observed using WISE/NEOWISE and Spitzer in NGC 2547-ID8, HD 166191, WD 0145+234, and some others systems); (b) in five optical systems with the normal stars (UU CrB, AZ Ori, FF Ori, IX Oph, CU Cnc; three of the five systems are binaries; seven single flares were observed in 1980–2009 having a 1-hour average duration, an amplitude up to $2^{\rm m}$, and an energy up to 10^{39} erg); (c) in three optical/hi-energy systems with a compact object (V404 Cyg, MAXI J1820+070, Swift J1858.6−0814; all the systems are binaries hosting a black hole or a neutron star as a component; a “forest” of tens of flares was observed, the flares having a subsecond duration, an amplitude up to $1\overset{\rm m}{.}6$, and an energy of the order of 10^{36} erg/s); (d) in the near-IR range in the 2MASS stars (hundreds of flares were found based on the statistical study of more then 1300 2MASS M dwarfs). The RFs are suggested to be produced by a collisional impact and destruction of asteroid-like bodies in exosystems. All the above data independently supports an idea that exotic red flares are actually a real and well-distributed phenomenon. Undoubtedly, the RFs serve more deeper and wider investigation, keeping in mind their direct connection to the manifestation of asteroids in exosystems.

Keywords: stars: flare, planetary systems; minor planets, asteroids: general

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1 Introduction

Protoplanetary and debris disks in exosystems are a natural laboratory to study terrestrial exoplanet formation processes. Such a study allows discovering a new exoworld population: exocomets and exoasteroids. The most comprehensive review on exocomets was made in Strøm et al. (2020). According to the review, four systems unambiguously demonstrate spectral and photometric features of exocomets, and 29 systems show possible exocomet evidence. For the first time, specific exocomet features were detected in the β Pic spectra (Ferlet et al. 1987). An analysis of about 1000 spectra of this system revealed about 6000 exocomet manifestations (Kiefer et al. 2014).

The Spitzer monitoring campaign to study solar-like stars with ages of 30–130 Myr and extreme debris disks revealed first exoasteroids. The aftermath of a collision of large (over 100 km in size) asteroid-like bodies observed in ID8 (2MASS J08090250−4858172) from NGC 2547 was reported in Meng et al. (2014). A detailed analysis of its IR variability allowed Su et al. (2018) to conclude about the presence of two impacts: on 2012 October 22 at a distance of 0.44 au and in early 2014 at a distance of 0.24 au (the corresponding orbital periods are 108 and 41.6 days, respectively). An analysis of 5-year (2012–2017) Spitzer observations of ID8 (together with P1121 from the M47 cluster) was made in Su et al. (2019). The long-scale Spitzer monitoring data for another two systems, V488 Per and HD 166191, were published in Rieke et al. (2021) and Su et al. (2022), respectively.

A close (less than 30 pc) white dwarf with a debris disk, WD 0145+234, was observed in 2010–2023 using three space observatories: WISE/NEOWISE, Spitzer, and JWST. Its significant and long-lasted IR brightening in 2018–2019 was detected in the WISE/NEOWISE data and interpreted as a tidal destruction of an exoasteroid in the disk of the dwarf (Wang et al. 2019). The follow-up observations of the white dwarf obtained using Spitzer and JWST support the exoasteroid breakup hypothesis (Swan et al. 2021, 2024).

To date, there are more than 5500 exoplanets, 33 systems with exocomets, and only 2–3 systems whose (space-based) IR variability is interpreted as exoasteroid manifestations. On the other side, it is expected that the small bodies in exosolar systems are much more populated and, correspondingly, more active. For example, $\sim$6000 exocomet manifestations per $\sim$1000 (ground-based) spectra were detected in β Pic (see above). If so, similar activity should be expected for the exoasteroids. A search for exoasteroid manifestations using archival ground-based observed data was undertaken and reported in this paper.

2 Red flares in the optical and near-IR bands: abundance and statistics

The main criterion to suspect exoasteroid traces in ground-based observations is a brightening or a flare in the near-IR or in the red part of the optical range. The data on such red flares (RFs) were published for five systems with the normal stars, three systems with the compact objects, and in a statistical study of flare activity for the 2MASS catalog stars.

RFs in the normal stars. Five systems hosting the normal stars have demonstrated (single) RFs. Chronologically, the RFs were observed in UU CrB (Olson 1980), AZ Ori (Mirzoyan et al. 1983; Melikian et al. 1984), FF Ori (Zakirov 1993, 1996), IX Oph (Ibrahimov 2019, 2020, 2022), and CU Cnc (Jiang & Qian 2011). Three of the five systems are binary: FF Ori and CU Cnc are eclipse binaries, and IX Oph is a spectral binary. A total of seven single flares were observed in the five systems (FF Ori and IX Oph showed two flares each, separated by about a 1 yr long interval). The first flare was observed in UU CrB in 1980, the last one in CU Cnc in 2009. All observations were obtained using 0.4–1.0 m aperture optical telescopes. The photographic pg(ubv) system was used to observe AZ Ori, the photoelectric five-color Stromgren–Crawford and Kron $uvby+I_{\mathrm{K}}$ system for UU CrB, the photoelectric Johnson $UBVR$ system for FF Ori and IX Oph, and the R-band CCD observations were made for CU Cnc (its 91-h CCD monitoring revealed four R flares, the largest one with a 73-min duration and a $0\overset{\mathrm{m}}{.}5$ amplitude was selected for the search).

The observed RFs in the normal stars have, on average, 1 h long duration (40 to 80 min), and the R-band amplitude varies from $0\overset{\mathrm{m}}{.}1$ (FF Ori) to almost 2^{m} (IX Oph). The available multicolor observations for four systems (excluding CU Cnc) demonstrate a red maximum and an inverse amplitude distribution for the RFs (for details about the color and amplitude see the above references). The flare energy estimated for UU CrB, FF Ori, and IX Oph ranges from 10^{36} to 10^{39} erg. The available multicolor data for the RFs in UU CrB, AZ Ori, and IX Oph were transformed to the Johnson system and plotted in the $(U-B)-(B-V)$ color diagram (Fig. 1).

RFs in the systems with compact objects. Three systems hosting compact objects have demonstrated (multiple) RFs. Chronologically, the multiple RFs were observed in V404 Cyg (Gandhi et al. 2016), MAXI J1820+070 (Gandhi et al. 2018; Paice et al. 2019), and Swift J1858.6−0814 (Paice et al. 2018; Shahbaz et al. 2023). All the systems are binaries and host a black hole or a neutron star as a compact object. There are two differences between the RFs in the compact object systems (COSs) and in the normal star systems (NSSs). First, all RFs in the NSSs are single (one flare per one object per one observing season), while the COSs almost always

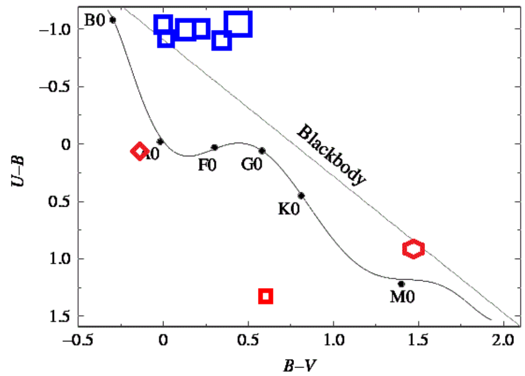

Fig. 1. Two-color diagram for three RFs observed in UU CrB (May 1980, red dimond), AZ Ori (Dec 1980, red hexagon), and IX Oph (Aug 1992, red square). The blue squares (taken from Gershberg 2015) designate flares of UV Cet-type stars.

demonstrate a "forest" of multiple RFs (tens of flares per one object per one observing run). Second, a typical duration of the RFs in the NSSs is about an hour, while the COSs have a subsecond typical duration of RFs. At the same time, the amplitude and energy for the RFs in the COSs and NSSs are comparable (an amplitude of $\sim 1\overset{m}{.}6$ for the Swift J1858.6−0814 most powerful flare and an energy of $\sim 10^{36}$ erg/s as estimated for the V404 Cyg flares).

For the first time, an important feature was observed (Fig. 2) in the optical curve morphology for the RFs in IX Oph (NSS, a flare on 1992 Aug 28) and in J1858.6−0814 (COS, a flare on 2018 Nov 09). Both RFs simultaneously exhibit a flare (brightening in the red band) and an antiflare (darkening in the blue part of the optical range). Such a phenomenon has not yet been reported for other types of flare systems. Generally, a comparison between the RFs in the NSSs and COSs looks as follows: a single hour-long powerful flare in the NSSs (the amplitude and energy up to 2^{m} and 10^{39} erg, respectively) versus a "forest" of multiple subsecond-long and equally powerful flares in the COSs (the amplitude and energy of the order of $1\overset{m}{.}6$ and 10^{36} erg/sec, respectively).

RFs in the statistical study for the 2MASS stars. A massive search for flares on low-mass stars using the SDSS and 2MASS catalogs and a multiwavelength and statistical analysis for the found flares were done in Davenport et al. (2012). So far, this study is unique due to its multiwavelength approach and representativeness among other studies on stellar flares from the UV to NIR ranges. Flare activity of $\sim$50 000 M dwarfs from the SDSS and 1321 M dwarfs from 2MASS has been studied. Hundreds of NIR flares were detected for the investigated M stars in 2MASS (details for the flare detection method and for the model used can be found in the original

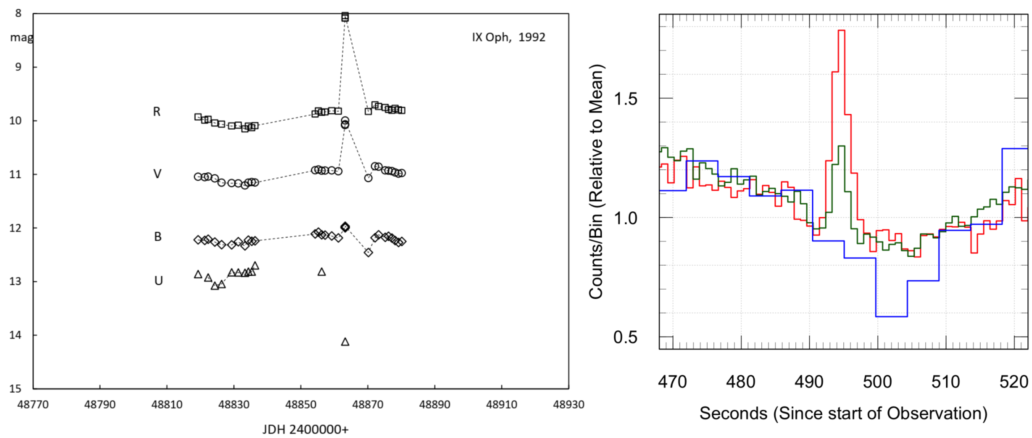

Fig. 2. Optical light curve morphology during the RFs in IX Oph (left panel, normal star system, 1992 Aug 28) and in J1858.6−0814 (right panel, compact object system, 2018 Nov 09 00:30:00 UT). Both curves demonstrate the simultaneous presence of a flare (brightening in the red band) and an antiflare (darkening in the blue part of the optical range).

paper). The averaged statistical data for all (optical and NIR) detected flares are listed in Table 2 and plotted in Fig. 6 in the paper. However, a comparison between the optical and NIR flares led to a strange result (a citation from paragraph 6, p. 67): "No simulated flares ... showed enough increase in flux to register ... a response in the JHK bands, however. The flare emission in the NIR must therefore be greatly influenced by physics not included in our ... model." It is supposed that the required physics could be found to explain the above result if one considers that a source for the 2MASS NIR flares is not the stellar but circumstellar matter (exoasteroids, etc.)

3 Summary

A search for exoasteroid manifestations using archival ground-based observed data was undertaken and reported in this paper. It was proposed that exoasteroids could be detected as exotic red flares (RFs). For the first time, the published data on the RFs obtained using optical/IR photometry was gathered and discussed. The RFs are suggested to be produced by a collision and destruction of asteroid-like bodies in exosystems. To date, the RFs have been observed:

(a) in IR space missions (1–2 yr long IR brightening observed using WISE/NEOWISE and Spitzer in NGC 2547 ID-8, HD 166191, WD 0145+234, and some others systems);
(b) in five optical systems with the normal stars (UU CrB, AZ Ori, FF Ori, IX Oph, CU Cnc; three of the five systems are binaries; seven single flares were observed

in 1980–2009 having a 1 h average duration, an amplitude up to 2^{m}, and an energy up to 10^{39} erg);

(c) in three optical/hi-energy systems with a compact object (V404 Cyg, MAXI J1820+070, Swift J1858.6−0814; all systems are binaries hosting a black hole or a neutron star as a component; a “forest” of tens flares was observed, the flares having a subsecond duration, an amplitude up to $1\overset{\mathrm{m}}{.}6$, and an energy of the order of 10^{36} erg/s);

(d) in the near-IR range in the 2MASS stars (hundreds of flares were found based on the statistical study of more then 1300 2MASS M dwarfs).

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