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Observations of high-amplitude optical transients AT2020ray and AT2020ugj discovered by MASTER robotic net

V.P. Goranskij[1], A.N. Burenkov[2], A.S. Moskvitin[2], O.I. Spiridonova[2], A.S. Vinokurov[2], V.V. Vlasyuk[2], A.V. Zharova[1]

[1] Sternberg Astronomical Institute, Moscow University, Universitetsky ave. 13, Moscow, 119234 Russia

[2] Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnij Arkhyz, Karachai-Cherkesia, 369167 Russia

We report photometry of two optical transients, MASTER OT J224524.92+211742.0 = AT2020ray and MASTER OT J213908.79+161240.2 = 2020ugj. Additionally, a spectrum of AT2020ray was obtained with the Russian 6-meter telescope, BTA. Both transients were classified as WZ Sge-type cataclysmic variables in superoutbursts. The superoutburst of AT2020ray was accompanied by multiple type B rebrightenings. In the bright state, both objects had strong UV excess.

The optical transient (OT) AT2020ray was discovered by MASTER-IAC auto-detection system at the position $22^{\rm h}45^{\rm m}24\overset{\rm s}{.}92$ $+21^\circ17'42\overset{''}{.}0$ (J2000) on 2020 Aug 10.10981 UT at the brightness level of $17\overset{\rm m}{.}0$ (the magnitude limit of the frame was $18\overset{\rm m}{.}1$). In the Sloan (SDSS) database, there is a faint star with a red magnitude of about $24\overset{\rm m}{.}4$, that means an outburst amplitude of $7^{\rm m}$ (Zhirkov et al., 2020).

Another OT, AT2020ugj, was discovered by MASTER-OAFA auto-detection system at the position $21^{\rm h}39^{\rm m}08\overset{\rm s}{.}79$ $+16^\circ12'40\overset{''}{.}2$ (J2000) on 2020 Sep 26.03850 UT, and its brightness raised from $16\overset{\rm m}{.}1$ to $15\overset{\rm m}{.}5$ during one hour after the discovery. There was no source in the SDSS database above the limit of $24\overset{\rm m}{.}3$ in the r band that means that the outburst amplitude was more than $8\overset{\rm m}{.}8$ (Pogrosheva et al., 2020). Igosai et al. (2020) took the spectrum of this transient on 2020 Sep 26.688 UT and classified the object as a WZ Sge-type dwarf nova in an early stage of its outburst. The spectrum showed blue continuum, strong emission of Hα, and weak emissions of Hβ and He II. Tanbo (2020) reported results of the star's photometric monitoring on two nights. There was a sign of superhumps with a period of $0\overset{\rm d}{.}0577 \pm 0\overset{\rm d}{.}0003$. This modulation could be early superhumps. The short period suggests that the system is a good candidate for a WZ Sge dwarf nova.

The information on the MASTER Global Robotic Network stations can be found in Lipunov et al. (2010). Discoveries of transient sources with so large amplitudes are very frequent. Only in 2020, the MASTER team reported 10 outburst discoveries with amplitudes exceeding $6^{\rm m}$ (not counting the two sources discussed in the present paper), and the nature of most of them remains unclear. Besides classical and dwarf novae, such objects may be asteroids, like MASTER OT J140356.92–095636.6 = AT2020mqn (Lipunov et al., 2020; Transient Name Server), or distant supernovae, like NSV 895 (Kato, 2015). Thus, follow-up observations of such transients, belonging to novae populations as well as to slowly moving objects, are of scientific interest.

We observed OT AT2020ray at the Special Astrophysical Observatory with the $UBV(RI)_C$ photometer based on an EEV 42-40 chip cooled to a temperature of –129°C, and with the MMPP $UBV(RI)_C$ photometer polarimeter based on a Raptor Photonics camera Eagle V with an CCD E2V 42-40 CCD working with a thermoelectronic transformer and an external liquid cooler. The devices were installed at the 1-meter Zeiss telescope. Furthermore, BVR_C photometry and a spectrum were obtained in the SAO with the SCORPIO multimode focal reducer at the Russian 6-meter telescope, BTA (Afanasiev and Moiseev, 2005). The photometric observations in the SAO were performed between 2020 Aug 13 and Nov 29. The accuracy of these observations varies between $0\overset{\mathrm{m}}{.}02$ and $0\overset{\mathrm{m}}{.}34$ in different filters in the magnitude range between 17^{m} and 23^{m}. Spectral observations were carried out on 2020 Aug 19 (JD 2459080.53) with the VPHG1200B grizm in the range of λ3800–5400 Å with the resolution of 5.5 Å. To minimize the dispersion of measured flux, we calculated an averaged spectrum with a moving averaging interval of 5 Å equal to the spectral resolution.

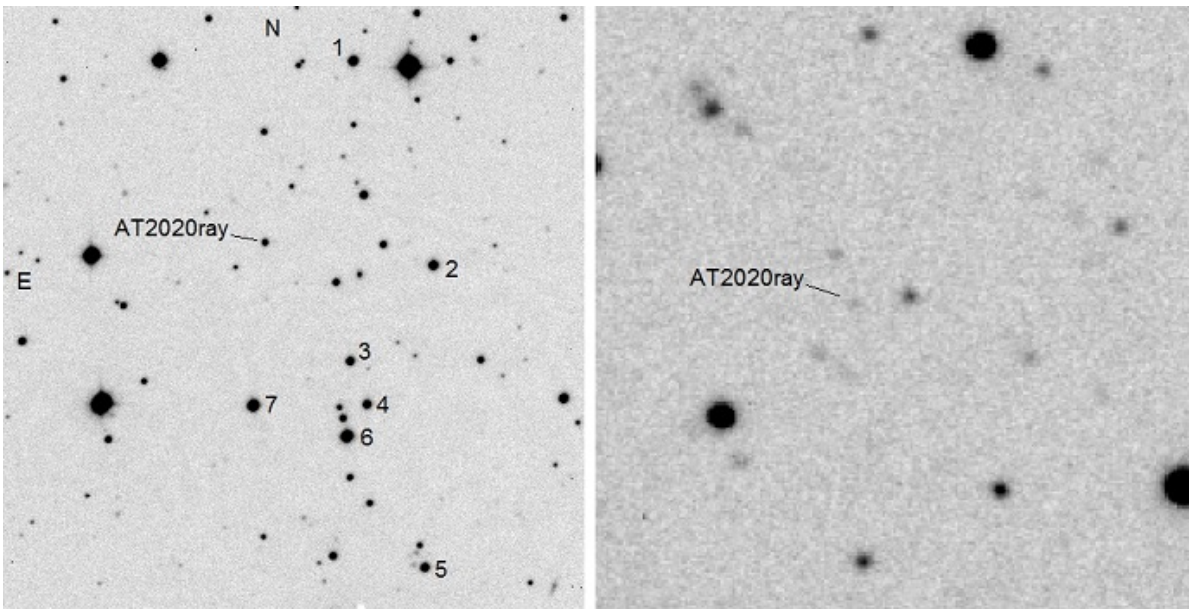

Figure 1. Images of AT2020ray. Left: $7'\times7'$ fragment of the frame taken with the SAO 1-meter Zeiss telescope on 2020 Aug 12 near the maximum brightness. Comparison stars are marked with numbers. Right: $1'.5\times1'.5$ fragment of the frame taken with the same telescope on 2020 Oct 12 when the star was faint. It was still brighter than in quiescent state by $1^{\mathrm{m}}.3$.

Additional $BV(RI_C)$ photometry of AT2020ray was taken at the Crimean Observational Station of the Moscow University with the 50 cm Maksutov meniscus telescope equipped with an Apogee Alta U8300 CCD at the prime focus. Observations were carried out between 2020 Sep 10 and 22. This telescope is not able to observe stars with magnitudes below 20^{m}. However, we collected long exposures and summed up the frames obtained within approximately an hour. Weak images of the transient are seen in most of the images at a low S/N ratio, in the range of 0.1–2. To measure such a faint star, we used the WinFITS software by V. Goranskij in the aperture mode. The software memorizes the positions of the aperture centers pointed on the OT, comparison and check stars, and locations of blank field measures in a file, and then reproduces these positions of apertures in the other frame superposing the comparison and the check stars with their aperture centers. This method allows us to measure the signal excess of a very faint star over

the background level. The accuracy of such measurements may be of several tenth of a magnitude and can reach a half magnitude.

The multicolor $UBV(RI)_C$ photometry of OT AT2020ugj was obtained with the Maksutov 50 cm telescope on 2020 Sep 26.74 UT near the light maximum. Later, the object was registered on 2020 Oct 18 with the SAO 1-meter Zeiss and MMPP, and on 2020 October 20, with the Crimean Station 60-cm Zeiss reflector equipped with an FLI KAF 39000 CCD at magnitudes of 19 and 20, respectively.

The comparison stars in the fields of both OTs in the *ugriz* AB95 spectrophotometric system can be found at the SDSS site[1]. We used the study of the *ugriz* AB95 system by Fukugita et al. (1996) to transform magnitudes of comparison stars into the Johnson–Cousins $UBV(RI)_C$ system, where magnitudes are related to α Lyr.

An image of AT2020ray near its maximum brightness, with the comparison stars, is presented in Fig. 1 (left). The right frame in this Figure is a deep photo of the star taken near the minimum brightness. The star is located against a dense background of distant galaxies. The magnitudes of comparison stars are given in Table 1. Photometric measurements of AT2020ray are presented in Table 2.

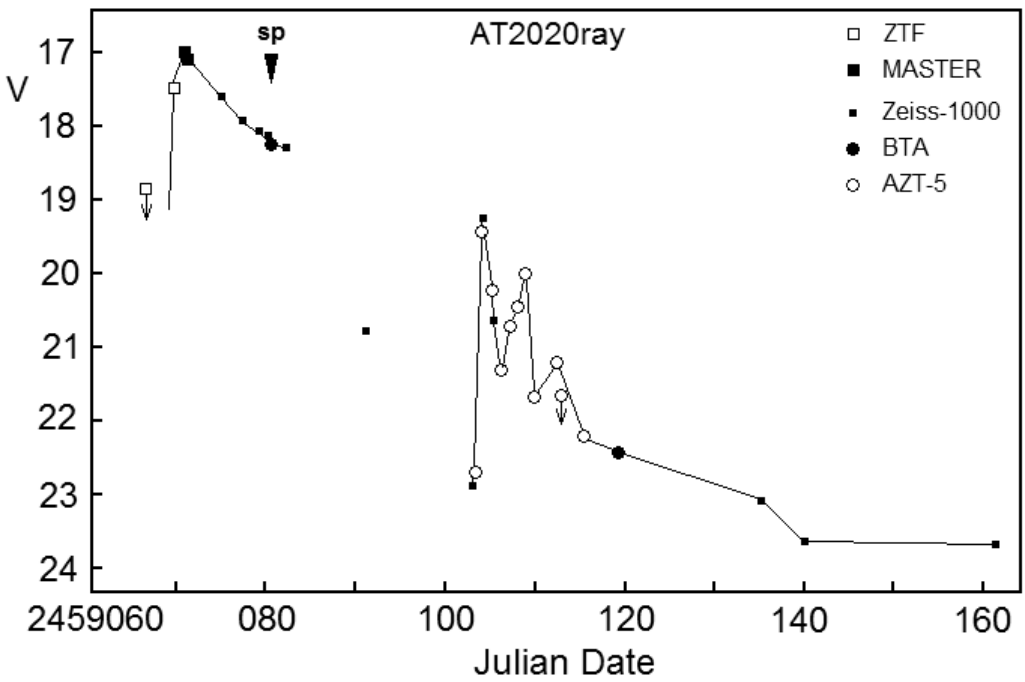

Figure 2. Light curve of AT2020ray in the V band. Symbols with downward arrows are upper brightness limits, when the star was invisible in the frame. The arrow 'sp' indicates the time when a spectrum was taken with BTA/SCORPIO.

The light curve of AT2020ray in the V band is shown in Fig. 2. We also plotted the ZTF pre-outburst r magnitude limit, r magnitude taken from the Transient Name Server, and MASTER unfiltered magnitudes by Zhirkov et al. (2020). The light curve shows a part of a typical superoutburst of an UGSU type variable in the time range between JD 2459069 and 2459082, and then, after a break of observations, multiple rebrightenings on JD 2459104 ($V = 19\overset{m}{.}29$) and 2459109 ($V = 19\overset{m}{.}97$). One more rebrightening was registered by us in the R band, JD 2459100 ($R_C = 20\overset{m}{.}47$). Such superoutbursts with rebrightenings are characteristic of the WZ Sge subclass of SU UMa (UGSU) stars. According to the

[1] http://skyserver.sdss.org/dr12/en/tools/chart/navi.aspx

Table 1: $UBV(RI)_C$ magnitudes of AT2020ray comparison stars

No.	U	B	V	R_C	I_C
1	16.87	16.79	16.12	15.71	15.28
2	18.17	17.37	16.32	15.70	15.17
3	18.98	18.02	16.78	16.02	15.34
4	17.99	17.62	16.76	16.23	15.71
5	18.46	17.66	16.62	16.00	15.45
6	16.29	15.99	15.23	14.77	14.32
7	15.96	15.93	15.33	14.96	14.58

Imada et al. (2006) classification of WZ Sge light curves, a light curve with multiple rebrightenings belongs to type B. Colors of the star were blue on the 4th day after the maximum: $U - B = -0\overset{\mathrm{m}}{.}70$, $B - V = 0\overset{\mathrm{m}}{.}15$, with a large UV excess of about $-0\overset{\mathrm{m}}{.}8$. The spectrum taken on the 9th day after the maximum (Fig. 3) shows blue continuum and wide shallow absorption Balmer lines with the full width of about 100 Å at zero redshift. The Hβ line is partially filled by emission. The He II 4686 Å line looks like a weak and wide emission merging with the C III/N III Bowen blend. This spectrum is typical of cataclysmic variables in outbursts and confirms the Galactic membership of this OT.

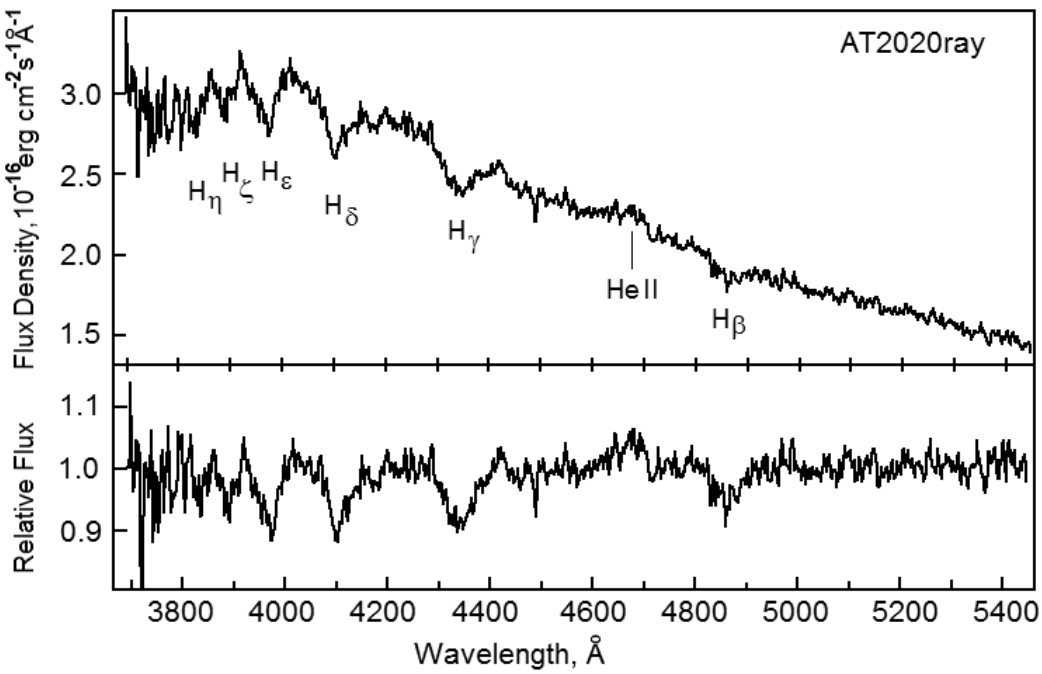

Figure 3. BTA/SCORPIO spectrum of OT AT2020ray. Top: calibrated spectrum in flux units. Bottom: normalized spectrum in the continuum units. The identification of spectral lines is given.

An image of AT2020ugj and its comparison stars is given in Fig. 4, $UBV(RI)_C$ magnitudes of comparison stars are given in Table 3. The light curve is presented in Fig. 5. Along with other observations taken with the SAO 1-meter Zeiss telescope, Moscow University Zeiss-600, and Maksutov AZT-5 telescope, we included data from MASTER, ZTF and ATLAS sky surveys. However, the observations are sparse and cover only 24 days.

21–30 days is a typical length of a superoutburst in WZ Sge type stars, so we cannot say anything about rebrightening using this material. Multicolor photometry taken on 2020 Sep 26, near the maximum light, shows the same blue colors and strong UV excess as for AT2020ray (Fig. 6) but a rather hotter black-body temperature of about 13000 K compared with 10000 K for AT2020ray.

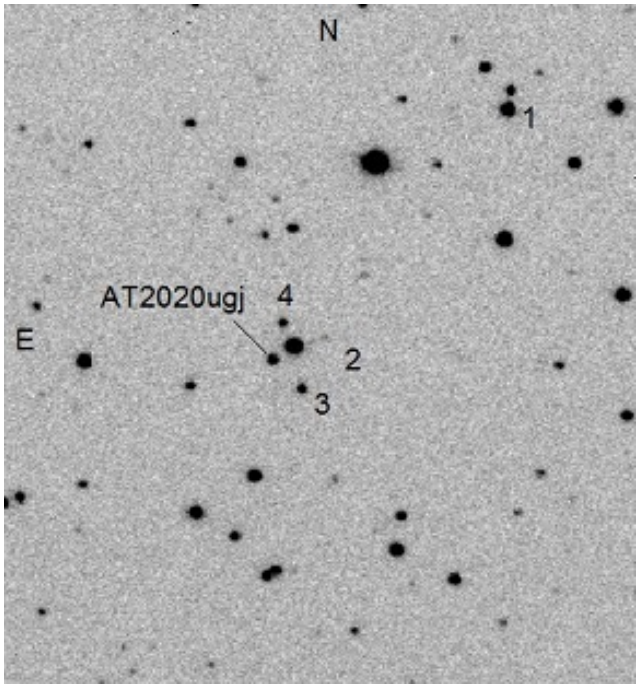

Figure 4. Image of OT AT2020-ugj. This is a $7\farcm5 \times 7\farcm5$ fragment of the frame taken on 2020 Sep 26 with the 50-cm Maksutov meniscus telescope of the Moscow University Crimean Station. Comparison stars are marked with numbers. The star No. 5 is located far beyond the borders of this image. Its co-ordinates are given in the remark to Table 3.

S. Howell and his colleagues were the first who paid attention to faint cataclysmic variables at high Galactic latitudes with extremely large outburst amplitudes. They picked out a group of "tremendous outburst amplitude dwarf novae", or TOADs (Howell et al., 1995), which is a synonym of WZ Sge dwarf novae. The most detailed review on this group of stars and their properties is given by Kato (2015). These stars are short-period binaries with a white dwarf and a cool late-subclass M dwarf or probably a brown dwarf; in the latter case, it is not seen in the optical spectrum. They are semidetached systems with accretion disks and have a low mass transfer rate. The radiation of the cool dwarf is located mostly in the infrared range. The typical mass ratio of components in these systems is about 0.08. White dwarfs give also small contribution to the common light in optics, and that is why the systems are so dim at the minimum brightness. The orbital periods of these systems are mostly shorter than 0.06 days, and half of them form a "period spike" of the period distribution of cataclysmic variables in the range between $0\overset{\mathrm{d}}{.}0553$ and $0\overset{\mathrm{d}}{.}0592$. Patterson (2011) showed that absolute magnitudes of outbursting dwarf novae were a good "standard candle" to estimate their distances, and this observational fact was confirmed by disk-instability modelling. Later, a weak dependence was found between absolute magnitudes and orbital periods. However, the orbital period range of WZ Sge-type dwarf novae is so small that $M_V(\mathrm{max}) = 5\overset{\mathrm{m}}{.}3$ is a good value for all of them. Note that these dwarf novae are fainter than the Sun even at the peak of their

Table 2: $UBV(RI)_C$ photometry of AT2020ray

JD hel. 24...	U	B	V	R_C	I_C	Tel. Dev.
59075.2183	17.02	17.75	17.61	17.68	17.58	SO
59077.5528	17.41	-	17.93	17.92	-	SO
59079.4447	-	18.28	18.08	18.04	17.98	SO
59080.4485	-	18.31	18.14	18.10	18.16	SO
59080.5223	-	-	18.24	-	-	6m
59082.4210	-	18.34	18.29	18.26	18.27	SO
59091.3281	-	(21.0	20.8	(21.3	21.6	SO
59093.3772	-	-	-	21.30	-	SO
59100.5408	-	-	-	20.47	-	SO
59103.1790	-	-	22.9	-	-	A5
59103.4562	-	22.2	22.7	20.77	20.33	SO
59104.2491	-	-	19.43	-	-	A5
59104.4025	-	19.49	19.29	19.24	19.42	SO
59105.2296	-	-	20.24	21.5	-	A5
59105.5119	-	20.72	20.65	20.34	20.39	SO
59106.1598	-	-	21.3	-	-	A5
59107.2211	-	-	20.76	-	-	A5
59108.2765	-	-	20.45	-	-	A5
59109.2669	-	-	19.97	-	-	A5
59110.2795	-	-	21.7	-	-	A5
59110.3726	-	21.36	-	21.02	-	SO
59112.4460	-	-	21.2	-	-	A5
59113.3427	-	-	(21.6	-	-	A5
59115.3746	-	-	22.21	-	-	A5
59119.2427	-	22.17	22.42	22.36	-	6m
59134.2605	-	23.0	0.00	23.2	-	SO
59135.2601	-	23.11	23.10	22.87	-	SO
59140.1741	-	23.52	23.65	22.73	22.50	MM
59162.2955	-	23.78	23.68	22.88	-	SO
59168.3128	-	23.90	-	-	-	SO
59181.2750	-	-	-	(22.8	-	SO
59182.2497	-	-	-	22.95	-	SO

Remarks on telescopes and devices (Tel./Dev.):

6m – BTA/SCORPIO;

A5 – AZT-5/Apogee Alta U8300;

MM – Zeiss-1000/MMPP photometer polarimeter;

SO – Zeiss-1000/UBVRI photometer.

brightness. Taking into account the Galactic absorption of $0\overset{m}{.}17$ for AT2020ray and $0\overset{m}{.}20$ for AT2020ugj, we get distances of 2.0 kpc and 1.0 kpc, respectively, for these stars. Thus, these stars are nearby objects in spite of their low brightness.

The high-amplitude superoutbursts of WZ Sge systems are recurrent, with a long recurrence time, from years to decades, the median time between superoutbursts being 15 years. The duration of superoutbursts is longer than that for SU UMa-type variables, and they last for several weeks. In superoutbursts, both WZ Sge and SU UMa variables show periodic variability with periods close to orbital ones, called superhumps. Periods of superhumps vary slowly in the course of a superoutburst. Short (normal) outbursts are frequent for the SU UMa-type stars but absent or rare for WZ Sge-type stars.

The presence of a white dwarf in such a short-period system means that a massive star in the primordial wide binary has passed the evolution stage of the red giant. At that time, a red dwarf was immersed into a common envelope with the giant for a long time and survived. The angular momentum of the orbital motion was lost through mass outflow in an equatorial belt (Webbink and Politano, 1993), dissipated with the extended red giant envelope (Paczyński, 1976), or lost through tidal friction (Eggleton, 1976). The mechanism of the momentum loss by the radiation of gravitation waves was supposed, too (Faulkner, 1971). A result of evolution is the emergence of a short-period pre-cataclysmic white dwarf – red dwarf binary from the common envelope. Numerous discoveries of WZ Sge-type outbursts by robotic telescopes suggest that this scenario takes place very often during the last stages of stellar evolution.

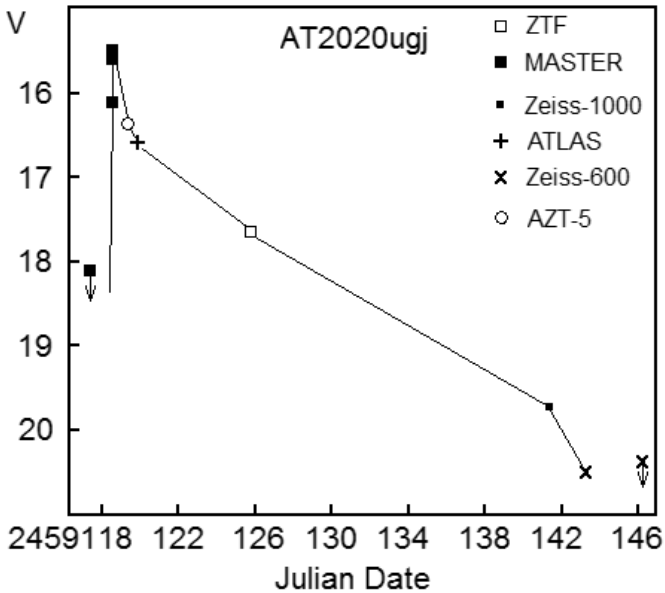

Figure 5. Light curve of AT2020uqj in the V band. The downward arrows mark upper limits when the star was invisible.

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Table 3: $UBV(RI)_C$ magnitudes of AT2020ugj comparison stars

No.	U	B	V	R_C	I_C
1	15.06	15.14	14.77	14.50	14.41
2	15.82	15.21	13.97	13.42	12.96
3	-	16.93	16.00	15.47	15.08
4	-	18.07	16.53	15.93	15.46
5*)	13.37	13.49	12.76	12.34	12.06

*) SDSS position 324°.86304 16°.34519. Outside Fig. 4.

Table 4: $UBV(RI)_C$ photometry of AT2020ugj

JD hel. 24...	U	B	V	R_C	I_C	Tel. Dev.
59119.2387	15.57	16.36	16.37	15.99	15.90	A5
59141.2976	-	-	19.72	-	-	MM
59143.2453	-	-	20.5	-	-	Z6
59080.4485	-	-	(20.4	-	-	Z6

Remarks on telescopes and devices (Tel./Dev.):

A5 – AZT-5/Apogee Alta U8300;

MM – Zeiss-1000/MMPP photometer polarimeter;

Z6 – Zeiss-600/FLI KAF 39000 CCD.

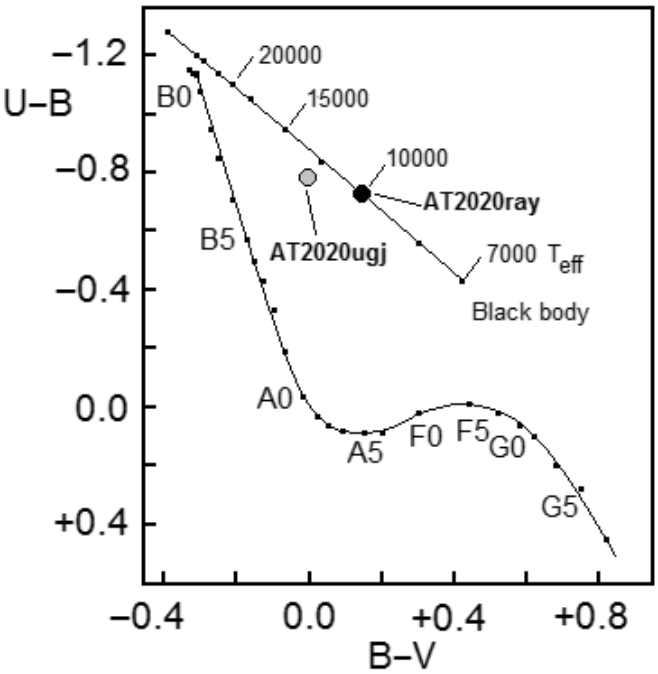

Figure 6. Location of AT2020ray and AT2020ugj in the $(U-B)-(B-V)$ diagram near the maximum light. Both stars have ultraviolet excesses relative to normal main sequence stars and are close to black body colors. AT2020ray location coincides with that of a black body at the temperature of 10000 K. AT2020ugj is hotter and is close to the location of a 13000 K black body.

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