The past photometric history of the FU Ori-type young eruptive star 2MASS J06593158-0405277 = V960 Mon

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Abstract

The known FU Ori-type young eruptive stars are exceedingly rare (a dozen or so confirmed objects) and 2MASS J06593158-0405277, with its 2014 outburst, is likely the latest addition to the family. All members have displayed just one such eruption in their recorded history, an event lasting for decades. To test the FU Ori nature of 2MASS J06593158-0405277, we have reconstructed its photometric history by measuring its brightness on Harvard photographic plates spanning the time interval 1899-1989. No previous large amplitude eruption similar to that initiated in 2014 has been found, as in bona fide FU Ori-type objects. The median value of the brightness in quiescence of 2MASS J06593158-0405277 is *B*=15.5, with the time interval 1935-1950 characterized by a large variability (~1 mag amplitude) that contrasts with the remarkable photometric stability displayed at later epochs. The variability during 1935-1950 can either be ascribed to some T Tau like activity of 2MASS J06593158-0405277 itself or to the also young and fainter star 2MASS J06593168-0405224 that lies 5 arcsec to the north and forms an unresolved pair at the astrometric scale of Harvard photographic plates.

Keywords: Stars: pre-mail sequence

1. Introduction

The FU Ori-type outburst of 2MASS J06593158-0405277 (hereafter '2MASS' for short) was discovered by T. Kojima on 3 Nov 2014 (Maehara et al. 2014). It has been recently given the variable star name V960 Mon (Kazarovets and Samus 2015). Inspection of older observations revealed the object was already brightening during the previous two months. No previous bright phase of this object was known. A low-resolution spectrum of 2MASS for 23 Nov 2014 (Maehara et al. 2014) shows no emission lines and only absorptions from Balmer, NaI, MgI, BaII and LiI in close resemblance to that of the prototype object FU Ori. Hillenbrand (2014) obtained on 9 Dec 2014 a high resolution optical spectrum, with the absorption lines showing an excellent match to that of an early F giant or supergiant and a P-Cyg profile for Hα indicating wind outflow. An infrared spectrum of 2MASS was obtained on 20 Dec 2014 by Reipurth and Connelley (2014), resembling that of a late-K to early-M star. Such a difference in the spectral classification is typical for FU Ori-type outbursts, with the spectral type becoming gradually later with increasing wavelength. This is a result of the inner warmer disk regions dominating the optical while outer cooler disk regions dominate in the infrared (Hartmann and Kenyon 1996). A high spatial resolution VLT/SINFONI infrared observation by Caratti o Garatti et al. (2015) shows that 2MASS is actually composed of two sources separated by 0.23 arcsec (~100 AU at the 450 pc distance estimated by Kóspál et al. et al. 2015), with a further possible and even closer third component.

FU Ori-type objects (FUORs hereafter) are pre-main sequence stars undergoing a large amplitude outburst that typically lasts for several decades (Herbig 1977). FU Ori itself rose in 1937 from 16.5 to 9.5 mag, where it has remained ever since, while V1057 Cyg - that erupted in 1969 rising from 16 to 10 mag - has been steadily declining but it is still several magnitudes brighter than its preceding quiescence (AAVSO database). Their basic structure has been modelled by Hartmann and Kenyon (1996). A young, low-mass (T Tauri) star is surrounded by a disk normally accreting at $\sim10^{-7}$ $M_{\odot}yr^{-1}$ onto the central star. This slowly evolving phase is punctuated by occasional FUOR outbursts, in which the the accretion rate from the disk onto the star

Table 1: The photometric comparison sequence around 2MASS J06593158 -0405277 used in the inspection of historical Harvard plates.

	RA	DEC	B	V	R_C	I_C
b	105.011879	–3.983185	10.359	10.086	9.871	9.462
c	105.014885	–4.084866	11.067	10.714	10.500	10.239
d	104.904816	–3.985026	11.485	10.851	10.455	10.004
e	104.733200	–4.052388	12.005	10.996	10.430	9.897
f	104.749748	–4.090763	11.952	11.011	10.472	9.932
g	104.910187	–4.024831	12.301	11.257	10.659	10.087
h	104.830132	–4.113718	12.300	11.678	11.334	10.948
i	104.843948	–4.035124	11.974	11.945	11.914	11.851
j	104.914253	–4.154183	12.859	12.427	12.095	11.779
k	104.908340	–4.158614	13.706	13.334	13.040	12.821
l	104.896210	–4.069036	13.910	13.526	13.339	13.122
m	104.855392	–4.134413	14.521	14.095	13.828	13.653
n	104.868362	–4.122244	14.699	14.210	13.890	13.510
o	104.914810	–4.077499	14.955	14.511	14.197	14.002
p	104.884598	–4.103065	15.309	14.864	14.550	14.233
q	104.918861	–4.107513	15.937	15.128	14.659	14.199
r	104.862259	–4.108619	16.717	15.935	15.553	15.215

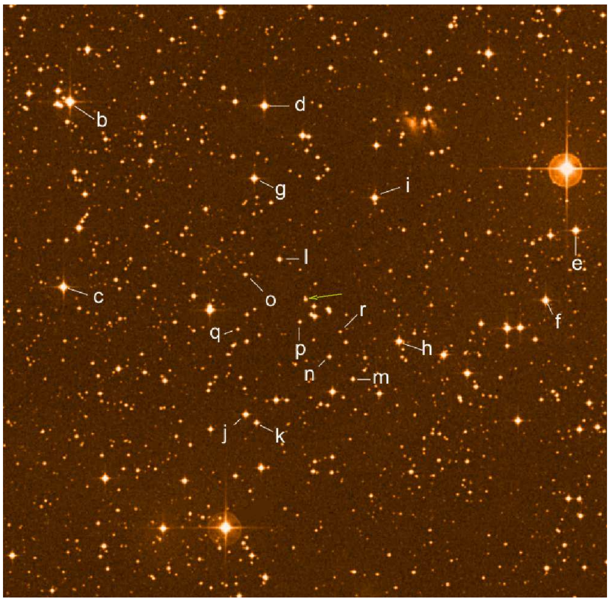

Figure 1: Identification of the photometric comparison sequence (cf. Table 1) around 2MASS J06593158-0405277, placed at the center of the picture and identified by the arrow (north up, east to the left, size 20 arcmin).

rises to $\sim10^{-4}$ $M_\odot yr^{-1}$. The disk becomes hot enough to radiate most of its energy at optical wavelengths, and it dumps as much as 0.01 $M_\odot$ onto the central star during a century-long FUOR episode. Mass is fed to the disk by the remnant collapsing protostellar envelope with an infall rate $\lesssim10^{-5}$ $M_\odot yr^{-1}$. During FUOR eruptions, high-velocity winds ($\gtrsim$300 km sec^{-1}) are generated that carry away about 10% of the accreted material.

FUORs are rare, with about only a dozen of them being currently confirmed according to Kóspál et al. (2015; the SIMBAD database lists such a classification for a total of 39 objects). Thus, any new addition to the family is relevant, as for 2MASS. The low-number statistics is still sensitive to differences inherent to the individual objects and the non homogeneous way they have been observed, with most of the studies focusing on only a few FUORs. So far, the known FUORs have displayed just one eruption in their recorded history, but their pre-discovery photometric behavior is sometimes undocumented. For this reason, we went to the Harvard photographic plate stack and directly inspected the available plates to the aim of reconstructing the photometric history of 2MASS prior to the 2014 outburst. The results are described in this paper.

2. Photometric sequence

To estimate on Harvard plates the brightness of 2MASS, we have extracted from the APASS all-sky photometric survey (Henden et al. 2012, Henden and Munari 2014, Munari et al. 2014) a local photometric sequence placed around 2MASS in a way convenient for visual plate inspection. The sequence is presented in Table 1 and identified in Figure 1, to the aim of assisting with the inspection of photographic plates at archives around the world other than Harvard.

3. Harvard plates

Our 2MASS target has a close and fainter companion, about 5 arcsec to the north, identified with 2MASS J06593168-0405224. The pair is marginally resolved on Palomar/SERC sky survey prints but it is not recognized as such by two separate entries in the USNO-B or GSC catalogs based on them. Both stars show a strong excess at infrared wavelengths from circumstellar dust (Reipurth and Connelley, 2014), and both emit in the X-rays (Pooley et al. 2015), suggesting that also the companion is a young star as 2MASS itself. At the plate scale of the astrographs used to expose the plates preserved in the Harvard stack, the pair cannot be separated and always appears as a single, unresolved star.

Table 2: *B* band brightness of 2MASS J06593158-0405277 on Harvard plates.

JD	series	numb	expt (min)	*B* (mag)	JD	series	numb	expt (min)	*B* (mag)	JD	series	numb	expt (min)	*B* (mag)
2428110.864	rh	6887	90	15.96	2429585.436	rb	9248	60	15.86	2432240.291	rb	14905	120	14.99
2428250.266	rb	6689	120	15.08	2429672.384	rb	9367	120	15.35	2432594.613	rh	14455	71	15.52
2428837.873	bm	687	50	15.10	2429686.541	bm	2171	54	14.99	2432884.468	rb	16030	120	15.73
2428838.860	rh	7836	65	15.50	2429699.513	bm	2208	33	15.35	2432887.807	rh	14855	140	15.80
2428919.667	rh	8046	60	15.51	2429930.874	bm	2883	63	14.75	2432940.309	rb	16109	120	15.80
2428926.650	rh	8058	61	15.65	2429937.856	bm	2918	56	14.99	2432977.364	rb	16149	120	15.85
2428927.641	rh	8064	60	15.65	2429938.523	rb	10111	120	15.89	2433190.587	rb	16508	120	15.59
2428959.365	rb	7738	120	15.59	2429941.834	rh	9985	85	14.99	2433243.772	rh	15210	131	15.73
2428982.535	rh	8198	60	14.90	2430263.589	rb	11051	120	16.08	2433708.365	rb	16862	120	15.75
2429224.539	rb	8389	120	14.93	2430314.453	rb	11180	120	15.85	2434007.706	rh	15804	74	15.39
2429245.747	rh	8643	70	14.90	2430325.472	rb	11214	120	15.80	2434029.308	rb	17030	120	15.39
2429278.662	bm	1119	63	14.65	2430673.527	rb	11892	120	15.80	2445373.960	dsb	993	30	15.37
2429318.553	bm	1199	52	14.99	2431523.359	rb	13491	120	15.93	2446436.040	dsb	1861	30	15.37
2429335.353	rb	8504	120	16.01	2431823.374	rb	14178	120	16.13	2446470.952	dsb	1881	30	15.36
2429528.594	rb	9166	120	14.99	2431886.277	rb	14271	120	15.80	2447589.895	dsb	2781	30	15.35
2429582.823	bm	1729	61	15.52	2431908.260	rb	14305	120	15.80					

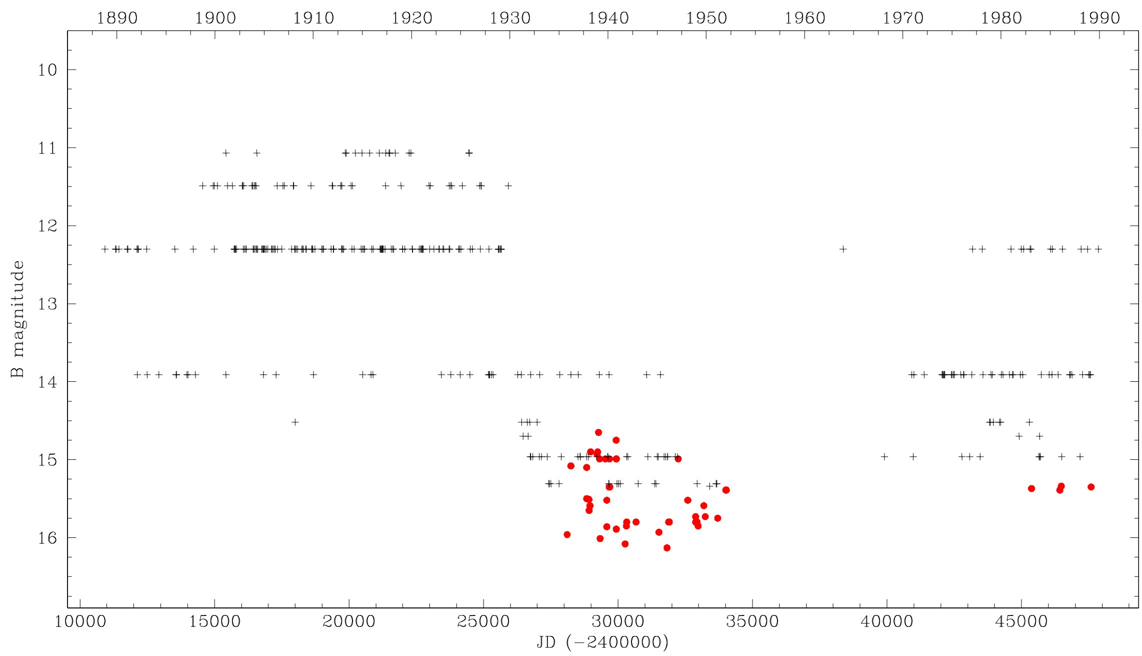

Figure 2: Historic *B*-band lightcurve of 2MASS J06593158-0405277 from Harvard plates. The dots mark the recorded brightness, the crosses are upper limits from shallower plates.

Thus, our measurements of the brightness of 2MASS on the Harvard plates actually refer to the combined pair.

Historic Harvard plates are almost invariably blue sensitive emulsions exposed unfiltered through lens astrographs. For cool objects like 2MASS, this combination results in a pass-band close to modern *B* band. Thus, on the Harvard plates that we inspected, the brightness of 2MASS was estimated against the *B*-band sequence of Table 1 and Figure 1. This, however, does not necessarely apply to much hotter objects, for which the emission in the *U* band is not negligible compared to that through the *B* band. For them, a correction factor has to applied to their brightness estimated on Harvard plates against a *B* band sequence (cf. the template case of the progenitor of nova KT Eri we have recently investigated on Harvard plates; Jurdana-Šepić et al. 2012, Munari and Dallaporta 2014). The correction factor depends on the stellar spectral energy distribu-

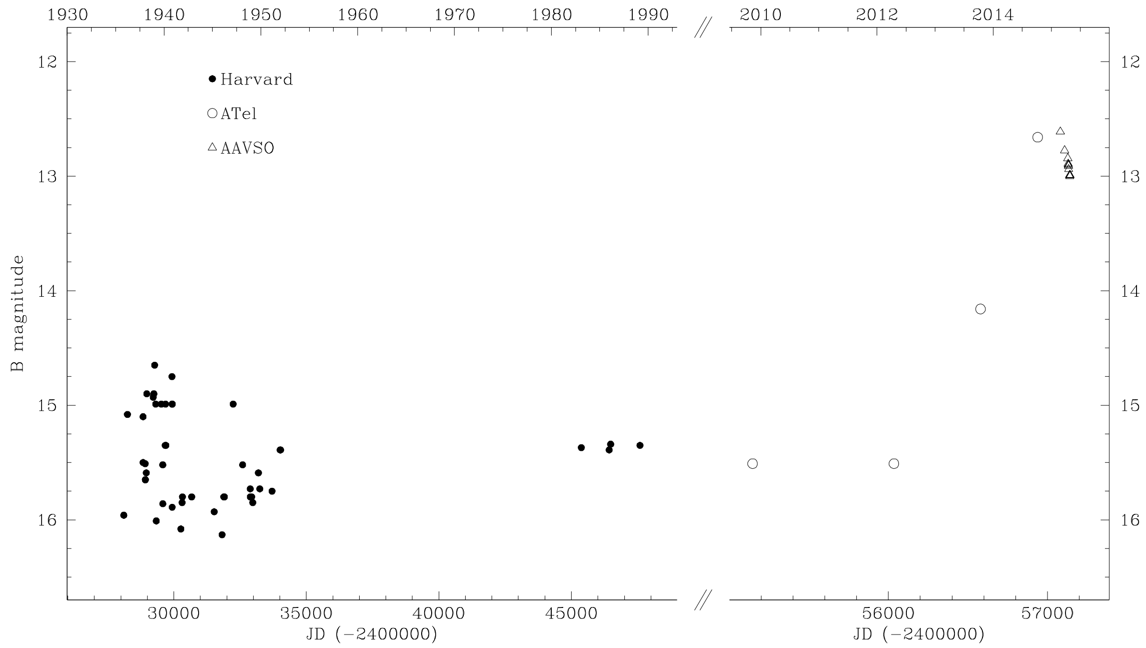

Figure 3: The *B*-band brightness of 2MASS J06593158-0405277 on Harvard plates compared with the *B*-band lightcurve during the 2014 outburst (see text for details). Note the break in the abscissae.

Table 3: Upper limits to the *B* band brightness of 2MASS J06593158-0405277 on Harvard plates (this long table is published in its entirety in electronic form only. A portion is shown here for guidance regarding its form and content).

JD	series	numb	expt (min)	lim. mag (B)
2426738.400	rb	2453	90	14.96
2426751.635	rh	3921	60	13.91
2426762.317	rb	2481	30	14.96
2426831.219	rb	2702	90	14.96
2426989.866	rh	4589	61	14.52
2427078.703	rh	4805	55	14.96
2427092.477	rb	3883	90	13.91
2427160.291	rb	3986	34	14.96
2427364.850	rh	5456	80	14.96
2427419.779	rh	5607	54	15.31
2427456.412	rb	4807	90	15.31
2427508.305	rb	4903	27	15.31

tion between the *B* band and the ultraviolet atmospheric cut-off, the atmospheric and objective lens transmission over the same wavelength, and the sensitivity as function of wavelength of the photographic emulsion.

Plates potentially covering the 2MASS field were selected for the Harvard general database based on their plate centres, angular extension and orientation on the sky. The plates were manually retrieved from the plate stack, placed under a high quality monocular lens and the area encompassing 2MASS and the surrounding comparison stars centred on the eyepiece. A total of 481 Harvard plates were selected for inspection. When viewed at the eyepiece, 103 of them turned out to be unsuited because of a range of problems (out of focus, too shallow exposure, damaged plate, etc.). Of the remaining 378 usable plates (spanning the time interval from 1889-1989), 2MASS was fainter than the limiting magnitude on 330 plates, and visible and measured on 47 of them. To check upon the accuracy of our measurements, after a week (to ensure full loss of our memory about them) we remeasured the brightness of 2MASS on these 47 plates. The median difference in the magnitude estimated in these two passes is 0.14 mag, so 0.07 mag from the mean value, which is a fair estimate of the error associated to our visual estimates, and in line with the intrinsic accuracy of photographic emulsions as photometric detectors. The results are presented in Tables 2 (positive detections, average of the two independent estimates) and 3 (upper limits to the brightness of 2MASS based on the faintest star of the photometric sequence still visible, this long table being available electronic only) and are plotted in Figures 2 and 3.

We have also inspected the original prints of the *Cart du Ciel* all-sky photographic survey available at the Asiago observatory. The 2MASS area is covered by a plate taken on 25 February 1908 at San Fernando Observatory. On this plate, star *"m"* of the local photometric sequence is clearly visible but 2MASS is not, which place an upper limit of 14.5 to the *B*-band brightness of 2MASS on that date.

4. Results

The results of our inspection of Harvard plates are presented in Figure 2, and fully support the uniqueness of its recent FUOR outburst. Apart from the uncovered Menzel's gap in the 50ies (during which photographic sky patrol was suspended at Harvard), the object has generally remained fainter than 14 mag in *B* band, and when detected the median value for its *B* band magnitude has been 15.5.

These results on 2MASS from Harvard plates are compared to photometry of the current FUOR outburst in Figure 3. Two sources for the recent data are considered. Once the outburst was announced, AAVSO observers acquired data in the *B* band (and other optical bands too), and these are plotted in Figure 3 as daily averages. They show a decline of about half a magnitude during the two months they cover before the conjunction with the Sun prevented further observations. The second source of recent data are the discovery and prediscovery observations by Maehara et al. (2014) and Hackstein et al. (2014). These observations have been carried out in the I_C band. To transform them into *B* band data, we applied a color index of $B-I_C$=+2.76 as derived from outburst observations by AAVSO observers. Given the nice agreement with Harvard and AAVSO data in Figure 3, this transformation looks reasonable. With some degree of extrapolation, Figure 3 suggests that until late 2012 / early 2013 2MASS was still in quiescence and that the rise toward maximum took about 1.5 years, a value typical of FUOR (Hartmann and Kenyon 1996).

A final comment is in order about the variability of ~1 mag amplitude displayed by 2MASS during 1935-1950 (cf Figure 3), which contrasts with the photometric stability at later epochs and the report by Hackstein et al. (2014) of a constancy in brightness within 0.05 mag of 2MASS during 2009-2012. The variability observed in 1935-1941 is much larger than the measurement errors (see previous section), and therefore appears real. It could either be ascribed to 2MASS itself and its probable T Tau behavior before the current FUOR outburst, or to the optical companion 2MASS J06593168-0405224 in blend with our target on all Harvard plates. Given the much fainter magnitude of the companion, if this is the one responsible for the activity recorded during 1935-1950, it must have varied by several magnitudes in order to affect the combined magnitude by ~1 mag.

5. Acknowledgements

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