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 ($\sim 1$ 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-main 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 ($\sim 100$ 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 $\sim 10^{-7} M_\odot$ yr$^{-1}$ onto the central star. This slowly evolving phase is punctuated by occasional FUOR outbursts, in which 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     | RC    | IC    |
|----------|-----------|-------|-------|-------|-------|
| 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| -3.85026  | 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| -4.24831  | 12.301 | 11.257 | 10.659 | 10.087 |
| h        | 104.830132| -4.13718  | 12.300 | 11.678 | 11.334 | 10.948 |
| i        | 104.849348| -4.05124  | 11.974 | 11.945 | 11.914 | 11.851 |
| j        | 104.914253| -4.154183 | 12.359 | 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| -4.103965 | 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 |

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 astographs 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  | B (min) | (mag) |
|--------|--------|------|-------|---------|-------|
| JD     | series | numb | expt  | B (min) | (mag) |
| JD     | series | numb | expt  | B (min) | (mag) |

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 necessarily 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 | exp (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         |
| 2427092.477 | rb     | 3883 | 90        | 13.91         |
| 2427160.291 | rh     | 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         |

The $B$-band and 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 pre-discovery 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.

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