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BVRI photometry of Nova KT Eri 2009 in quiescence and the 752 day period

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H I G H L I G H T S

- Accurate and extensive BVRI photometry during post-outburst quiescence.
- Revision to the use of B-band magnitudes to calibrate old plates.
- Quiescence brightness and variability similar across 2009 outburst.
- Too bright in quiescence for the distance estimated via MMRD relations.
- Confirmation and revised ephemeris for the 752 day period.

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We obtained extensive new BVR_CI_C photometry of Nova KT Eri 2009 over a 539-day interval during the post-outburst quiescence, from 30 September 2011 to 22 March 2013 (days +684 to +1223 past maximum). The median magnitudes we measured are $B = 15.24$, $V = 15.00$, $R_C = 14.75$ and $I_C = 14.49$. A marked variability is present (total amplitude of $\Delta V = 1.6$ mag). Accounting for a generally overlooked correction to blue photographic magnitudes calibrated against modern B-band data, we found that mean brightness and amplitude of variability of KT Eri in quiescence are the same before and after the 2009 nova outburst. The distance to KT Eri derived from standard relations involving the absolute magnitude at maximum vs rate of decline (MMRD), is ~6.5 kpc. At such a distance, to fit the $BVR_CI_C + JHK$ flux distribution of KT Eri in quiescence requires an 8200 K blackbody with a radius of 3.5 $R_\odot$, which is vastly larger than the radius of typical accretion disks of CVs and classical old novae (0.1 $R_\odot$). The distance to KT Eri could therefore be much shorter than expected from MMRD relation. We also observed a new eclipse-like minimum to occur right on time following the 752 day period suspected to modulate the quiescence of KT Eri before the outburst. The nature of this period remains unclear. The faintness of KT Eri at infrared wavelengths ($K = 14.1$) precludes it from being the orbital period of the accreting WD, because in such a case the Roche lobe filling companion would be a cool giant shining at K~9 mag.

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1. Introduction

Nova KT Eri was discovered at $V = 8.1$ on 25 November 2009 by Itagaki (2009), at the time when that part of the sky emerged from the conjunction with the Sun. Early spectroscopic report indicated a He/N class and a FWHM of 3400 km/s for the Hα emission line (Maehara, 2009). Subsequent inspection of data from SMEI (Solar Mass Ejection Imager) led Hounsell (2010) to reconstruct the unseen early outburst phases. SMEI first detected KT Eri on November 13.12 at 8.4 mag, during the rapid rise toward maximum that was reached at V = 5.4 on November 14.67 UT, eleven days before the discovery by Itagaki. SMEI light-curve indicates that the decline started immediately after the nova reached its maximum brightness, and was a very fast one with t_2=6.6 days. Preliminary reports on the early spectroscopic and photometric evolution were provided by Ragan (2009), Rudy et al. (2009), Bode (2010), Imamura and Tanabe (2012), and Hung et al. (2011).

Radio observations were obtained by O'Brien et al. (2010) with various telescopes that caught KT Eri on the rising part of the radio light curve. Super-soft X-ray emission was observed by Bode (2010), who noted the presence of large variability (a factor of ~20 in ~3 h) and similarities with the recurrent nova LMC 2009a. Subsequent X-ray observations by Beardmore et al. (2010) showed a reduced amplitude of variability and the presence of a 35 s period. The same periodicity was also observed during the super-soft phase of the recurrent nova RS Oph (Osborne et al., 2006), that Beardmore et al. (2010) suggest could originate from

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pulsations in the residual nuclear-burning white dwarf envelope. X-ray spectral observations with Chandra were presented by Ness et al. (2010).

Infrared photometry and spectroscopy covering the first 100 days of the outburst of KT Eri were discussed by Raj et al. (2013). They confirmed the similarity with He/N and recurrent novae, also in the limited amount of ejected mass, and from the profile of emission lines (briefly discussed also by Shore et al. (2013)) they suggested the presence of a bipolar flow. The line profiles and their temporal evolution were modelled in detail by Ribeiro et al. (2013). They found the ejecta to have a dumbbell structure with a ratio between the major and minor axis of 4:1, with an inclination angle of 58^{+6}_{-7} degrees and a maximum expansion velocity of 2800 ± 200 km/s.

The progenitor of KT Eri is a 15 mag star, which sets the total amplitude of the nova outburst to about 9.5 magnitudes. The limited amplitude, fast decline and large ejection velocities are properties shared by many recurrent novae (Warner, 1995). The majority of recurrent novae have evolved donor stars (sub-giants or giant stars) and long orbital periods (Darnley et al., 2013), whereas classical novae have low main sequence secondaries and much shorter orbital periods (hours).

Jurdana-Šepić et al. (2012, hereafter J+12) searched the Harvard plate archive and measured the progenitor of the nova on 1012 plates dating from 1888 to 1962. No previous outburst was found. The quiescence brightness appeared modulated by eclipse-like events occouring every ~737 days (or its alias at ~750). J + 12 noted how such long periodicities are comparable to the orbital period of recurrent novae of the symbiotic type, like RS Oph and T CrB, that contain a Roche lobe filling cool giant. Other long periodicities are present in J + 12 data and still others have been elsewhere reported from different data sets. White light (un-filtered) data obtained by the Catalina Sky Survey between 17 January 2005 and 18 November 2009 were inspected by Drake (2009). They found, with a low statistical significance, a possible periodicity of ~ 210 days and provided a folded light-curve for the data that suggests a large amplitude (~1 mag). McQuillin et al. (2012) reported on SuperWASP white-light (unfiltered) observations of the progenitor that were carried out a year before the outburst. Their data show a slow modulation, with a time scale of about 78 days. Hung et al. (2011) searched for periodicity their photometric data that covered the decline of KT Eri from day 272 to day 473 past optical peak (for an interval Δt=201 days). They reported the presence of a 56.7 day periodicity, but no tabular data or folded light-curves were provided.

In this paper we report about our extensive optical photometry covering the first two observing seasons after KT Eri returned to quiescence following the 2009 nova outburst. We have been primarely motivated by (1) to verify if the pre-outburst eclipses were still visible after the outburst, quantify the associated change in brightness and color, and confirm their very long period, the longest known among old novae; (2) to compare the brightness and level of activity before and after the outburst, which has been recently studied for a large number of other novae, and (3) to derive the optical + IR flux distribution and absolute magnitude of KT Eri in quiescence to constrain the nature of the progenitor and that of the companion responsible for the eclipses.

2. Observations

BVR_CI_C photometric observations of KT Eri after it returned to quiescence where obtained with ANS Collaboration telescope N. 30. The long term photometric and spectroscopic monitoring program carried out by the network of telescopes operated by ANS Collaboration is described by Munari (2012) and Munari and Moretti (2012). The telescope used for the observations presented in this paper is a 0.30-m Meade RCX-400 f/8 Schmidt-Cassegrain located in Cembra (Trento, Italy). The CCD is an SBIG ST-9, 512×512 array, 20 μm pixels ≡ 1.72″/pix, providing a field of view of 13′×13′. The B filter is from Omega and the UVR_CI_C filters from Custom Scientific. The transformation to the standard system was carried out by means of a local BVR_CI_C photometric sequence accurately calibrated by A. Henden (private communication) against Landolt (2009) equatorial standards, and checked against $BVg'r'i'$ values in APASS Data Release N.7 (Henden et al., 2013). Our observations are listed in Table 1 and plotted in Fig. 1. They cover a total time span of 539 days, from 30 September 2011 to 22 March 2013 (from day + 684 to day + 1223 past the optical maximum as fixed by the SMEI satellite pre-discovery observations). The quoted errors are the total error budgets (i.e. the quadratic sum of the Poissonian noise, the calibration noise and the uncertainty in the transformation from the istantaneous local photometric system to the standard system).

3. On the offset in zero point of historical and modern observations

Robinson (1975, hereafter R75) studied the pre-outburst light-curves of eleven novae and concluded that: 5 out of 11 novae showed pre-eruption rises in the years before eruption, one nova (V446 Her) showed a much larger variability before the outburst than after it, and all but one (BT Mon) of the novae have the same quiescent magnitudes before and after the outburst. Robinson's work remain the only one investigating pre-outburst novae until Collazzi et al. (2009, hereafter C+09) revisited the issue by studing a larger sample of objects that includes also those originally considered by R75. C + 09 concluded that, contrary to R75 the amplitude of variability of V446 Her and the brightness of BT Mon were the same before and after the outburst. Furthermore, C + 09 found no significant change in variability across 27 nova eruptions, and for 39 novae the brightness before and after the eruption was the same. Only five novae appeared much brighter after the outburst than before it (it is now known that in these novae the white dwarf remained trapped for years in stable H-burning conditions, as betrayed by the simultaneous super-soft X-ray emission, the extremely high ionization of optical spectra and the orbital light-curve modulated by heavy irradiation of the secondary).

The comparison of our post-outburst photometry with the pre-outburst data by J + 12 allows to test on KT Eri some of the conclusion drawn by R75 and C + 09.

To estimate the brightness of KT Eri on Harvard plates, J + 12 used the same photometric comparison sequence that we adopted for our CCD post-outburst observations. Similar to C + 09, the ulfiltered, blue-sensitive Harvard plates were measured by J + 12 against the modern B-band sequence, which was established by CCD observations calibrated on the Landolt (2009) equatorial standards. The median value of KT Eri brightness measured by J + 12 before the nova outburst is B = 14.59 (cf. left panel of Fig. 4). After the outburst we found instead B = 15.24 (cf. right panel of Fig. 4), a difference of 0.65 mag. Does this necessarely mean that KT Eri was brighter before than after the outburst? Actually not.

Fig. 2 shows a recent spectrum of KT Eri obtained on 6 January 2013 with the Asiago 1.22 m reflector equipped with a B&C + CCD spectrograph. Its appearance is typical of all the other spectra we observed during the quiescence following the 2009 nova eruption, and that will be studied elsewhere. The continuum is hot (~8100 K), with a prominent Balmer continuum in emission, and comparatively weak emission lines exception made for the extremely strong HeII 4686 Å. Overall the spectrum resembles those of cataclysmic variables (CVs). Fig. 2 also shows the transmission

Table 1
Our photometry of KT Eri after it returned to quiescence (the table is published in its entirety in the electronic edition of the journal and in the web-page www.ans-collaboration.org; a small portion is shown here for guidance regarding its form and content).

HJD	date (UT$_\circ$)	B (±)	V (±)	R_C (±)	I_C (±)
5835.649	2011 10 01.149	15.175 0.023	14.948 0.013	14.668 0.017	14.424 0.020
5836.643	2011 10 02.143	15.400 0.022	15.171 0.017	14.914 0.020	14.641 0.023
5837.628	2011 10 03.128	15.352 0.019	15.209 0.014	14.908 0.017	14.618 0.020
5838.626	2011 10 04.126	15.234 0.019	15.041 0.015	14.752 0.020	14.508 0.020
5845.607	2011 10 11.107	15.556 0.024	15.222 0.017	15.006 0.019	14.683 0.023
5863.593	2011 10 29.093	15.727 0.016	15.425 0.012	15.157 0.014	14.872 0.017
5875.512	2011 11 10.012	15.457 0.037	15.131 0.021	14.925 0.026	14.547 0.025
5878.499	2011 11 12.999	15.251 0.028	14.990 0.021	14.697 0.019	14.479 0.026
5881.528	2011 11 16.028	15.317 0.017	15.118 0.011	14.871 0.014	14.576 0.015
5883.491	2011 11 17.991	15.062 0.013	14.855 0.010	14.527 0.010	14.297 0.010

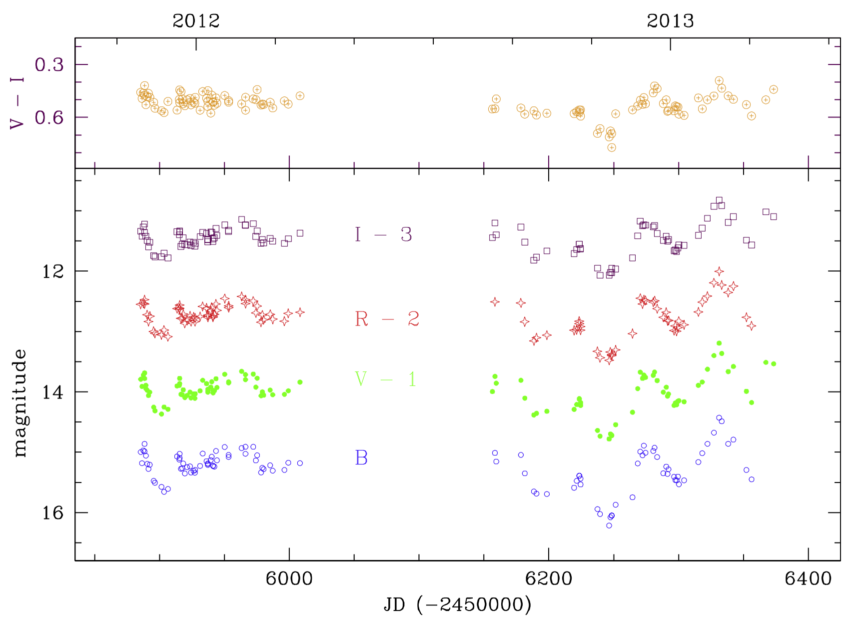

Fig. 1. Our observations of KT Eri from 30 September 2011 to 22 March 2013 (from day +684 to day +1223 past maximum as fixed by SMEI satellite pre-discovery observations). The light-curves are shifted for clarity (−1 mag for V, −2 for R_C, and −3 for I_C).

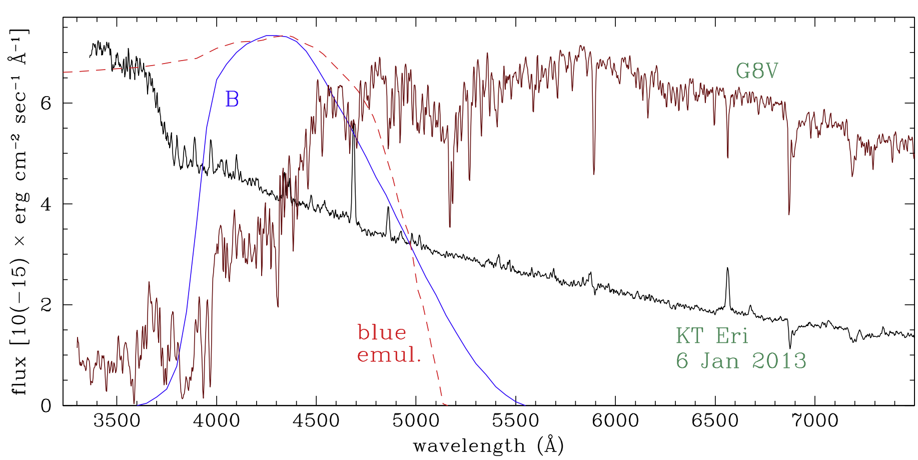

Fig. 2. An absolutely fluxed spectrum of KT Eri in quiescence obtained with the Asiago 1.22 m telescope compared with the sensitivity profile of Landolt's B band and of classical blue photographic emulsions. The spectrum of a G8V star as representative of typical field stars is plotted for reference.

of Landolt B band and the sensitivity of blue photographic plates of the type used for Harvard observations. In addition, Fig. 2 also shows for reference the spectral energy distribution of a G8V star, which is the average spectral type for high galactic field stars with a V magnitude around 15 (from standard Besancon models of the Galaxy stellar populations, Robin et al., 2003). The B band sequences used by C + 09 were built from field stars around the novae, irrespective of their color (i.e. energy distribution), and J + 12 did the same to estimate the brightness of KT Eri on Harvard plates. Thus the comparison stars used by J + 12 (and by C + 09 for their novae) were on average (much) cooler than the nova, and of a spectral energy distribution similar to that of the G8V star in Fig. 2. It is quite obvious from Fig. 2 how, on unfiltered blue emulsion plates, KT Eri would appear much brighter than the G8V field star even if the two have the same B-band magnitude, because of the large ultraviolet leak of the unfiltered emulsion compared to proper filtered B-band. How much brighter? The answer depends on the transmission of the unfiltered telescope optics. If they transmit uniformly down to the ultraviolet atmospheric cut-off, the difference would be 1.5 mag for the conditions depicted in Fig. 2. The exact transmission profile of the many different astrographs used over the time to expose the plates preserved in the Harvard archive is however unknown. Assuming they were of the long-pass type and transmitting above ~3550 Å, the correction to J + 12 magnitudes would compensate the 0.65 mag offset with post-outburst B-band observations above noted (cf. central panel of Fig. 4).

We can therefore conclude that, by improving upon C + 09 and J + 12 calibration procedures – by properly accounting for the differences between unfiltered blue emulsion and proper B band magnitudes – the *apparent* 0.65 mag offset between pre- and post-outburst brightness of KT Eri is reduced, possibly nulled. This has the benefit of healing an apparent peculiarity of KT Eri compared with other novae studied by C + 09. It would be interesting to evaluate how much and for how many novae in the C + 09 sample this effect, neglected by them, would be important.

4. Absolute magnitude and flux distribution of KT Eri in quiescence

By application of the standard absolute magnitude at maximum vs rate of decline (MMRD) relation, the distance to KT Eri has been variously estimated to lay between 6 and 7 kpc (Ragan, 2009; Rudy et al., 2009; Bode, 2010; Imamura and Tanabe, 2012; and Hung et al., 2011). Considering the calibration spread inherent in the MMRD and the cosmic dispersion (e.g. della Valle, 1991), the range of distances applicable to KT Eri widens from 5 to 8 kpc. Such a long distance coupled with the 15 magnitude in quiescence calls for an intrinsically bright progenitor, much brighter that classical old novae.

As discussed in the previous section, the quiescence brightness of KT Eri across the 2009 outburst remained probably unchanged. We feel therefore appropriate to combine our post-outburst optical photometry ($B = 15.24$, $V = 15.00$, R_C=14.75 and I_C=14.49) with 2MASS pre-outburst infrared data ($J = 14.619$, $H = 14.159$, and $K = 14.092$), to derive the flux distribution of KT Eri in quiescence. The WISE infrared space mission, while scanning the all sky, detected KT Eri with all its four bands (W1 at 3.35, W2 at 4.6, W3 at 11.6, and W4 at 22.1 μm) but this occoured during the nova outburst. The progenitor was too faint in the far infrared to be observed by IRAS.

The flux distribution of KT Eri in quiescence is presented in Fig. 3, after correction for the minor $E_{B-V} = 0.08$ reddening estimated by Ragan (2009) to affect the nova. It looks real bright. As a comparison, we may consider SS Cyg, perhaps the most popular disk-dominated prototype CV. Its quiescence magnitude is $V = 12.4$ and its distance is 114 ± 2 pc (Miller-Jones et al., 2013). Pushed at the 6.5 kpc distance estimated for KT Eri, it would shine at a feable ~21 mag, about 6 mag fainter. The huge luminosity of KT Eri in quiescence is also confirmed by the results of trying to fit it with the energy distribution of normal stars. Adopting intrinsic J, H, K data from Koornneef (1983), B, V, R_C, I_C from Bessell (1990), and absolute magnitudes from Sowell et al. (2007), we can closely fit the flux distribution of KT Eri in Fig. 3 with that of an A7 III star at 5 kpc, or that of an A7 III/II star at 8 kpc, bracketing the range of distances estimated for KT Eri. Such a star would be characterized by a temperature of ~8100 K and a radius of ~3 $R_\odot$ if the nova is at a distance of 5 kpc, or ~5 $R_\odot$ at 8 kpc (Bertone et al., 2004; Straizys and Kuriliene, 1981). The fit with a plain blackbody would provide a temperature of 8200 K and a radius of 3.5 $R_\odot$ for a distance of 6.5 kpc.

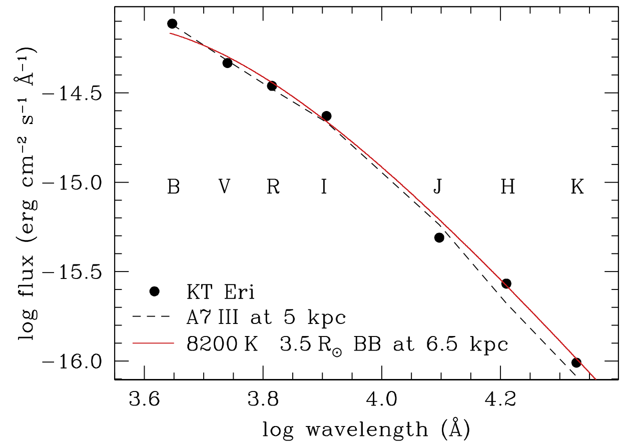

Fig. 3. The dereddened spectral energy distribution of KT Eri in quiescence is fitted by that of an A7 III star at 5 kpc or that of a plain black body of 8200 K temperature and 3.5 solar radii placed to a distance of 6.5 kpc.

The bottom line is that – if we assume valid the distance derived from MMRD relations – the dimension of the hot source in KT Eri during quiescence is vastly larger than that of accretion disks of normal CVs and classical old novae, that have typical radii of the order of 0.1 $R_\odot$. This further implies that the orbital period and orbital separations are much larger, and the absolute magnitude much brighter than those of normal CVs and classical old novae.

5. The 752 day period

The main periodicity found by J + 12 on their pre-outburst data was either ~737 days or its alias at ~750, in the form of regularly spaced sharp minima. A new minimum was recorded by our post-outburst photometry, as marked in the right panel of Fig. 4. Combining with the J + 12 data, our new minimum refines the period to 752 days, following the ephemeris

$$\mathrm{Min}(B) = 2456244(\pm 2) + 752(\pm 2) \times E \qquad (1)$$

The data in Table 1 (and their graphical representations in Figs. 1 and 4) show during such minima KT Eri becomes fainter by Δmag=0.5 and redder by $\Delta(V - I_C) \approx +0.15$ mag. The color change, the constant drop in magnitude and the marked regularity of the minima, argue in favour of eclises occouring along a 752 day orbital period.

Although attractive, an eclipse scenario constrats with some of the properties displayed by KT Eri.

In their modeling of the emission line profiles during the nova outburst, Ribeiro et al. (2013) found the ejecta of KT Eri to have a dumbbell structure with an inclination angle of 58^{+6}_{-7} degrees, probably too low to allow for eclipses.

The most important points are however others: who is reponsible for the eclipses? and is the companion able to fill its Roche lobe ?.

Whatever is passing in front of the hot source during eclipses, it is intercepting a sizeable fraction of its projected surface and it is cooler but not opaque. The minimum in Fig. 1 is "V" shaped, and not flat bottomed, meaning that the dimension of the eclipsing body is comparable (or larger) than the hot source. A K0 IV subgiant star has a radius (~3 $R_\odot$) similar to that of the hot source, and if during eclipses it intercepts about half of the area of the hot source, the drop in magnitude and change in color would be those observed. An isolated K0 IV sub-giant whould shine at $B = 18.2$, $V = 17.3$, I_C=16.2, $K = 15.3$ at the distance and reddening of KT Eri,

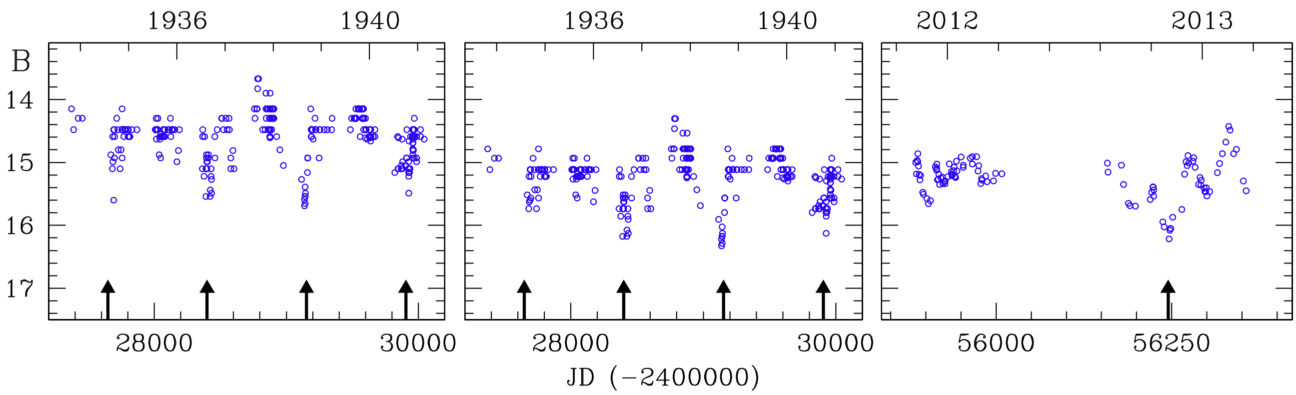

Fig. 4. *Left:* a portion of the historical blue lightcurve of KT Eri as derived by Jurdana-Šepić et al. (2012) from Harvard plates. *Center:* the same data as at left this time corrected for the shift in zero point discussed in Section 3 and the associated Fig. 2. *Right:* Our post-outburst *B*-band data. The arrows point to minima occouring with a 752 day periodicity following ephemeris (1).

faint enough to avoid impacting appreciably out-of-eclipse observations.

However, by no means a K0 IV sub-giant could fill its Roche lobe in an orbit so wide to require 752 days to complete. This could be achieved by a cool giant of the type present in symbiotic binaries and the recurrent novae RS Oph and T CrB (Mikołajewska et al., 2003; Munari, 2012) but the resulting flux distribution would be completely different from that shown in Fig. 3. In fact, according to the infrared survey by Whitelock and Munari (1992), the average absolute magnitude of the cool giants in symbiotic stars is $M_K \simeq -5$. At a distance of 6.5 kpc, such a giant would shine at $K \sim 9$, while 2MASS measured $K = 14.1$ for KT Eri. On the other hand, if the flux distribution of KT Eri in Fig. 3 is due to an accretion disk, the huge dimensions of such a disk would require to transfer mass at very high rate, of a type achievable only via Roche lobe overflow.

6. Concluding remarks

All this rests on the distance to KT Eri derived by the application of the standard MMRD relation. KT Eri should largely deviate from it and come much closer to us to alleviate the problems with the high brightness in quiescence, which requires an oversized accretion disk that radially extend for several solar radii (an order of magnitude wider than in normal CVs), and a suitable donor star to feed mass at high rate to sustain it.

Irrespective of the issue on distance, the 752 day period and the associated eclipses remains puzzling. It cannot be the orbital period of the accreting WD, because it would require the presence of a cool giant donor star, and this would be in sharp contrast with the faintness of the KT Eri at infrared wavelengths. We could speculate that the eclipses trace the presence of a third body in the system, orbiting at a great distance the central accreting and close binary where the 2009 nova outburst occurred. A triple system would be quite rare though, perhaps unique among known novae.

It is clear that more observations are required to shed light on this intriguing system. We plan to continue our photometric monitoring for at least the next two observing seasons. This will allow to cover the next eclipse on the 752 day period (scheduled for early December 2014) and to accumulate enough data over a long time span to investigate the presence of other periodicities. In particular, we plan to carry out long, uninterrupted monitoring sessions (combining telescopes distributed over a wide range of longitudes) to search for short periodicities, of the order of hours or days and much closer to those typical of CVs and old classical novae. Establishing the correct orbital period, would also fix the dimensions of the hot source (accretion disk), and this in turn would constrain the distance to KT Eri and allow to test if the MMRD relation fails or not for this nova.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.newast.2013.07.008.

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