

# A Naked-eye Optical Transient

Yue Zhao

Department of Physics, Lanzhou University, Lanzhou, China, and

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada

Patrick B. Hall, Paul Delaney, J. Sandal

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada

## Abstract:

A previously unknown optical transient has been observed in the constellation Bootes. The transient flared to brighter than 5th magnitude, which is comparable to the visual magnitudes of the nearby stars  $\pi$  Bootes and  $\sigma$  Bootes. This article describes the relative astrometry and photometry work we have done regarding the transient, which we provisionally designate Tr Boo.

## Introduction:

Distant astronomical sources normally invisible to the naked eye which transiently brighten by more than a magnitude to naked-eye visibility ( $V < 6$ ) are of considerable scientific interest. Specific examples include SN 1987A (peak  $V=2.96$ , Hamuy et al. 1988), GRB 080319B (peak  $V=5.3$ , Cwiok et al. 2008, Bloom et al. 2009), and possibly OT 060420 (apparent peak  $V=4.7$ , Shamir & Nemiroff 2006). Cataclysmic variable eruptions and flares on M dwarf stars can also in principle create naked-eye transients. M dwarf flares can have peak magnitude increases of  $\Delta V=6$  (Stelzer et al. 2006, Kowalski et al. 2013) and even  $\Delta V=9$  (Stanek et al. 2013) or  $\Delta B=9.5$  (Schaefer 1990). Cataclysmic variables such as classical novae or dwarf novae of the WZ Sge subtype can have magnitude increases up to  $\Delta V=7.5$  magnitudes (Harrison et al. 2004). Note, however, that the so-called stellar superflares on Sun-like stars produce less than one magnitude of brightness increase (Schaefer et al. 2000).

In part because of the rarity of reports of naked-eye transients, current limits on the rate of their occurrence on the sky are not strong (Shamir & Nemiroff 2009). Current and future large-area sky surveys will reveal more and more of these bright transients. Until then, studies of the transient naked-eye sky must rely on whatever images are available.

At York University, students in the introductory Natural Sciences course on Astronomy have taken photographs of assigned constellations each fall for over a decade. Here we report the details of our discovery (Zhao et al. 2013) of a naked-eye transient in photographs taken by one of those students.

## Discovery:

The constellation Bootes was observed from Brampton, Ontario, Canada (79.7667 W, 43.6833 N) by J. Sandal on the evening of 2012 September 25 local time (MJD 56195; UTC 2012 September 26) using a Sony DSC-W570 18.2 Mpix handheld camera. These observations reveal an unknown object flaring to brighter than 5th magnitude, comparable in brightness to  $\pi$  Bootes and  $\sigma$  Bootes (hereafter pi Boo and omi Boo). The transient was between 20 and 30 degrees above the horizon at the times of observation.

There are two photographs taken on the night of observation suitable for analyzing the properties of the transient. Image DSC1875 (Figure 1) had an exposure time of 2 seconds, and stars in it possess a slightly elongated point spread function. Image DSC1861 had an exposure time of 0.125 seconds, and stars in it appear as complicated trails due to camera motion. Information on the two images is given in Table 1; the pixel scale was determined from the separation of pi Boo and omi Boo.

A third photograph (DSC1864), taken in between the other two at 00:23:14 (UTC), does also show the transient to be present. However, its poor point spread function and low resolution of about 300 arc seconds per pixel makes it useless for detailed analysis. All we can conclude from it is that the transient is not brighter than pi Boo in that image.

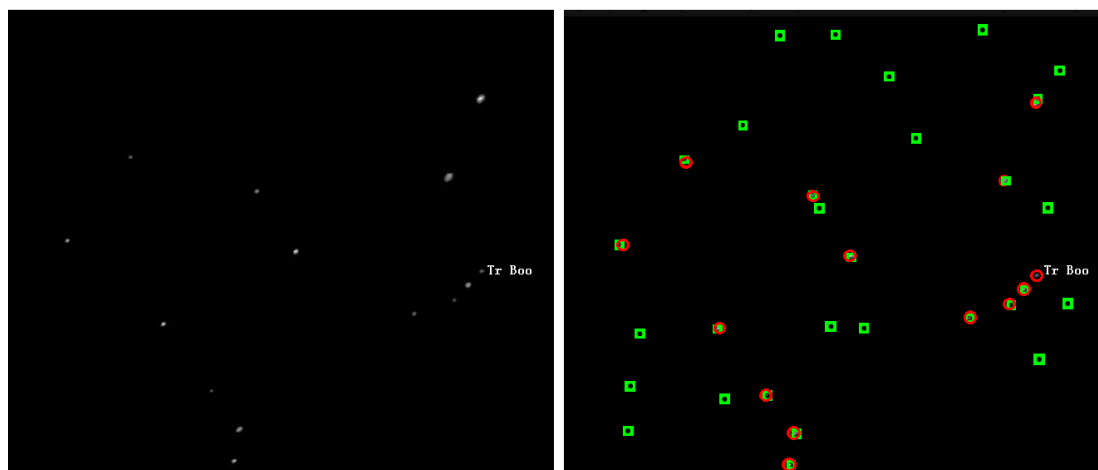


Figure 1: The image on the left is the original image DSC1875; north is at the left and east at the bottom. The constellation of Bootes is easily recognized. The image on the right is a slightly modified version of the red-green overlay output from astrometry.net. The symbols show the consistency of catalog object (squares) with objects detected on the image (circles). The single circle near the right edge is Tr Boo.

Tr Boo and its neighbors pi Boo and omi Boo are approximately equally spaced in a straight line on the sky with pi Boo in the middle and Tr Boo to the west, as seen in the close-up images in Figure 2.

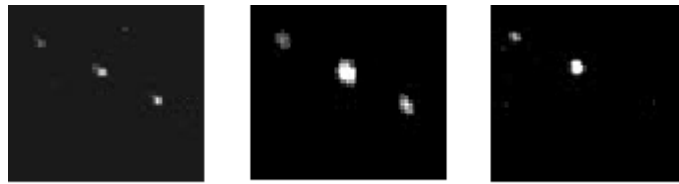


Figure 2: We show omi Boo, pi Boo and Tr Boo in our two images side by side (DSC1861 on the left and DSC1875 in the middle), rotated and magnified to the same scale, with north up and east to the left. The third image of the same region (right) is from the Palomar Observatory Sky Survey blue plate, magnified to the same scale.

The two pictures taken at different time with different rotation angles of the camera on the sky show that Tr Boo has an unchanged position relative to pi Boo and omi Boo. That excludes the possibility that Tr Boo is a reflection of Arcturus: if Tr Boo was such an artifact, it would have appeared at a different location on the sky when the camera was rotated.

#### All Sky Camera Searches:

We searched for the transient around omi Boo and pi Boo on images from the all sky camera operated by The Liverpool Telescope Project (Steele et al. 2004) on the island of La Palma, Spain. We scrutinized images taken between 19:41:14 and 20:05:14 on September 25th 2012 (UTC), which is several hours before the transient was observed in Ontario. Because of moonlight, we smoothed, shifted and combined several images together before seeking around Bootes for the transient. We did not find any object at the anticipated position with brightness comparable to omi Boo and pi Boo, from which we concluded that those images were taken before the transient brightened to the magnitude observed later.

We also examined images from the all sky camera archives at the Kitt Peak National Observatory and MMT Observatory (Pickering 2006). The earliest available images are from approximately UTC 02:00 on September 26th 2012. They do not show the transient, but the limit on its brightness is only  $V > 2.2$  from Kitt Peak (that is, fainter than alpha CrB) and worse on the lower-resolution MMTO images.

Scrutiny of the Liverpool all sky camera images taken the next night (UTC September 26th 2012 between 19:40:13 and 20:04:15) also shows no sign of the transient.

#### Position Measurement:

In image DSC1861, the stars have the shape of a seeing disk trailed in a complicated pattern due to camera motion. We used IRAF (Image Reduction and Analysis Facility) task “imedit” to isolate only the sharpest part of each object trail.

We calculated the coordinates of Tr Boo via a local linear transformation between pixel and equatorial coordinate systems, using the known coordinates of pi Boo and omi Boo. Our approach assumes the two coordinate systems are locally Cartesian near pi Boo, with the equatorial system having only a rotation angle and a scale difference relative to the pixel system. We solved for the coordinates of Tr Boo on the processed image DSC1861 and the image DSC1875 separately using the IRAF task “geomap” with the parameter “fitgeo=rscale”. These coordinates and their weighted average are given in Table 2.

#### Magnitude of the Transient:

On our images, the transient Tr Boo was of similar brightness to omi Boo but not as bright as pi Boo (which is a blended binary). omi Boo and pi Boo have nearly identical V-band magnitudes ( $V=4.61$  and  $V=4.51$ , respectively), but in the B band omi Boo ( $B=5.56$ ) is fainter than pi Boo ( $B=4.59$ ).

The relative magnitudes of omi Boo and pi Boo in our images are consistent with the camera responding to the average flux in the B and V bands. We used those average fluxes with the V band zeropoint to calculate "BV" magnitudes for omi Boo and pi Boo (4.98 and 4.55, respectively). In both of our images, we measured the magnitude of Tr Boo relative to omi Boo and pi Boo and averaged to obtain the "BV" magnitude and associated RMS uncertainty of Tr Boo shown in Table 3.

The decline of about one magnitude in the half an hour between our images is less steep than observed in gamma-ray bursts (Bloom et al. 2009). The decline is consistent with the range seen in flares on M stars during the gradual decay phase after peak brightness (Kowalski et al. 2013). If Tr Boo was an M dwarf flare, a fast rise phase may have been missed wherein it could have been a magnitude brighter than in our first image.

We obtain an upper limit to the magnitude of the transient approximately four hours before its detection based on an average image from the Liverpool all sky camera. We shifted 10 images to align pi Boo in all of them, subtracted a heavily smoothed version of each image from itself, and then averaged those background-subtracted images together. Tr Boo is not detected in the average image, and because omi Boo is the faintest object detected on the average image, the magnitude of Tr Boo must be larger than that of omi Boo. This magnitude limit is shown in Figure 3 with an error

bar extending off the plot, while the two measured magnitudes of Tr Boo are shown as points with error bars.

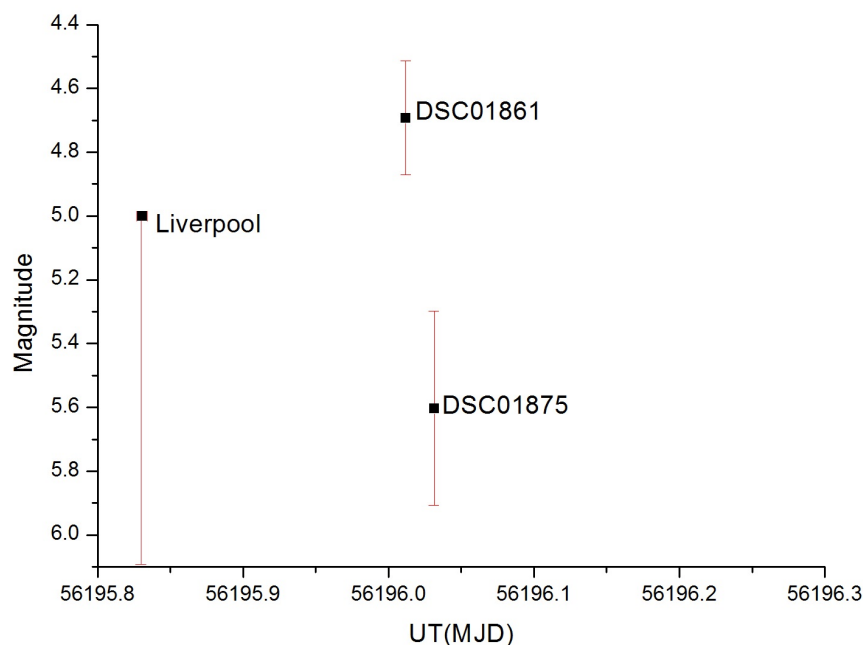


Figure 3: The magnitude of the transient at three different times. Note that the downward error bar on the Liverpool point means the transient's magnitude can be any value larger than 5.

#### Candidate Identifications for Tr Boo in Quiescence:

No known variable star is listed in the General Catalog of Variable Stars (Samus et al. 2010) within one degree of the transient. There are 3 stars that may be responsible for the transient when we search for candidates on SIMBAD centered on the calculated coordinates within a radius of 5 arcmin. Information on these 3 candidates, plus one other identified in the SDSS, are listed in Table 4, including their distance from Tr Boo in units of the random uncertainty (sigma) on the position of Tr Boo. Objects labeled in Table 3 are shown in a finding chart in Figure 4.

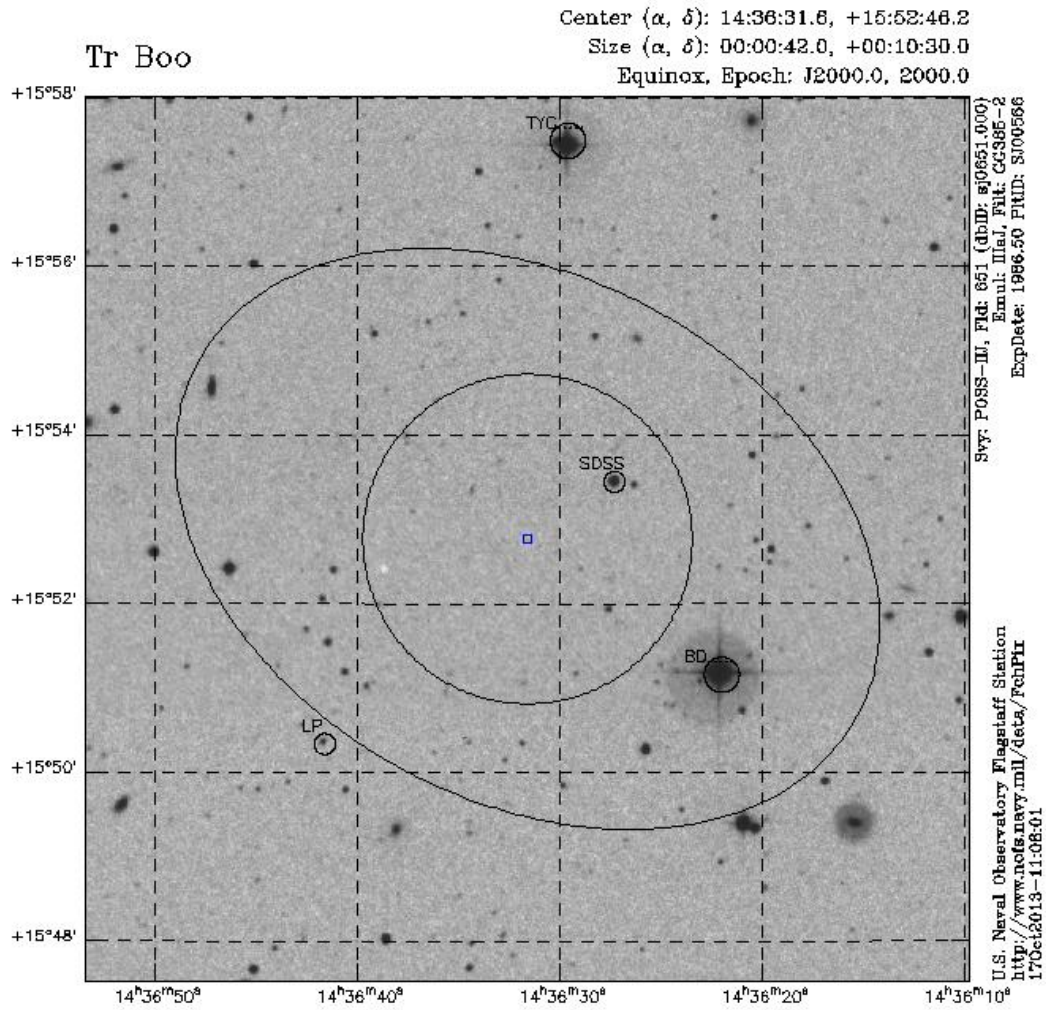


Figure 4: The box on this finding chart shows the weighted average position of Tr Boo. The circle shows the 3-sigma random uncertainty on its position. The ellipse incorporates both the 3-sigma random uncertainty and the 3-sigma systematic uncertainty (from the uncertainty on the pixel scale) on the position of Tr Boo, added together linearly (not in quadrature). The four objects discussed in the text as possible counterparts are labeled by their IAU prefix.

We used the databases of the CRTS (Catalina Real-time Transient Survey; Drake et al. 2009) and the ASAS (All Sky Automated Survey; Pojmanski 1997) to search for photometric light curves of these objects.

The object SDSS J1436+1553 (SDSS J143627.19+155326.8 = ASAS 143627+1553.5) was taken into consideration because of its relative proximity to Tr Boo. In the CRTS, this object has a constant magnitude around 14.0, which is consistent within the errors with the result given by the ASAS.

The red, high proper motion star LP 440-48 (Luyten 1981) has a magnitude of 15.9 in the CRTS, with no sign of variability. It is not found in the ASAS.

When comparing the photometry results from the CRTS and ASAS on the objects BD +16 2617 and TYC 1477-341-1, there emerged a large discrepancy. There are no conspicuous changes in their magnitudes judging from the ASAS light curves, but the CRTS results suggest three to four magnitudes of variability in both objects. In fact, CRTS photometry data for these objects are untrustworthy because the objects are often saturated.

We also searched for variable objects within a radius of 5 arcmin around Tr Boo. We found one object (CSS J143625.1+155102) with apparent variability which, however, is due to its proximity to a much brighter star. There are no useful data available in ASAS for this object.

We examined cutouts of the CRTS images at the location of Tr Boo (kindly provided by A. Drake), but found no evidence for an uncatalogued variable object in them.

Examination of the POSS-I and POSS-II plates within a 6 arc minute radius of the transient's coordinates did not reveal any objects with dramatic variability. (Note that the POSS-I O plate has at least six point-like defects within a 6 arc minute radius which are spurious, as they do not correspond to the positions of any objects in the SDSS images of the region.)

Examination of GALEX images of the field did not reveal any objects with unusual ultraviolet-optical colors. The star BD +16 2617 is much brighter in the UV than TYC 1477-341-1, but both stars have UV-optical colors consistent with expectations for stars with their optical colors. The star LP 440-48 is not detected by GALEX, and the star SDSS J1436+1553 is barely detected.

Examination of the HEASARC X-ray and gamma-ray satellite databases did not reveal any X-ray sources near the position of the transient, nor any gamma-ray burst consistent with its location and time of appearance.

## Conclusion:

The optical transient Tr Boo flared to naked-eye brightness for at least half an hour, but was not at naked-eye brightness several hours before the observation. Database searches at its position yield no unambiguous identification of a quiescent counterpart of this transient, but do identify several candidates. A flare on the high proper motion, probable M dwarf star LP 440-48 could have produced Tr Boo, but the amplitude of the flare would be an unprecedented 11.3 magnitudes, as compared to the previous record amplitude of 9.5 magnitudes (Schaefer 1990). Tr Boo could be an outburst from a previously unrecognized cataclysmic variable identified with LP 440-48 or one of two brighter stars in our error circle. If the latter is the case, the outburst would be

6.8 to 7.3 magnitudes, consistent with the known range of CV outburst amplitudes (Harrison et al. 2004). However, none of the candidate stellar counterparts of Tr Boo have shown any credible evidence of previous variability in the ASAS or CRTS. Spectroscopy of the possible counterparts of Tr Boo is needed as a next step to identifying its quiescent counterpart and determining the nature of this remarkable event.

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Tables:

Table 1

Image Name	UTC of Observation	Exposure Time	Pixel Scale (arcsec/pixel)
DSC1861	2012-09-26 00:17:54	0.125 sec	146.49±1.94
DSC1875	2012-09-26 00:45:50	2 sec	85.27±2.25

Table 2

	RA/degrees	DEC/degrees	RA	DEC
DSC1861	219.1292±0.0122	15.8928±0.0122	14:36:31±0:03	+15:53:34±0:44
DSC1875	219.1417±0.0237	15.8300±0.0237	14:36:34±0:06	+15:49:48±1:25
Wt. Avg.	219.1317±0.0109	15.8795±0.0109	14:36:31.6±0:02.7	+15:52:46.2±0:39.1

Table 3

Image	UTC	Magnitude
Liverpool	2012-09-25 19:51:14-20:00:03	>5
DSC1861	2012-09-26 00:17:54	4.7±0.2
DSC1875	2012-09-26 00:45:50	5.6±0.3

Table 4

Object	V Magnitude	Distance (arcsec)	Distance (sigma)	RA	DEC
Tr Boo	4.70	0	0	14:36:31.60	15:52:46.20
SDSS J1436+1553	13.99	75.5	1.93	14:36:27.19	+15:53:26.83
BD +16 2671	11.49	169.3	4.33	14:36:21.97	+15:51:09.47
LP 440-48	15.96	205.2	5.25	14:36:41.59	+15:50:20.20
TYC 1477-341-1	12.03	284.8	7.28	14:36:29.56	+15:57:29.50