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DISCOVERY OF THE PREDICTED 2010 ERUPTION AND THE PRE-ERUPTION LIGHT CURVE FOR RECURRENT NOVA U SCORPII

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ABSTRACT

We report the discovery by B. G. Harris and S. Dvorak on JD 2455224.9385 (2010 January 28.4385 UT) of the predicted eruption of the recurrent nova U Scorpii (U Sco). We also report 815 magnitudes (and 16 useful limits) on the pre-eruption light curve in the *UBVRI* and Sloan r' and i' bands from 2000.4 up to 9 hr before the peak of the 2010 January eruption. We found no significant long-term variations, though we did find frequent fast variations (flickering) with amplitudes up to 0.4 mag. We show that U Sco did not have any pre-eruption rises or dips with an amplitude greater than 0.2 mag on timescales from one day to one year before the eruption. We find that the peak of this eruption occurred at JD 2455224.69 ± 0.07 and the start of the rise was at JD 2455224.32 ± 0.12. From our analysis of the average *B*-band flux between eruptions, we find that the total mass accreted between eruptions is consistent with being a constant, in agreement with a strong prediction of nova trigger theory. The date of the next eruption can be anticipated with an accuracy of ±5 months by following the average *B*-band magnitudes for the next ~10 years, although at this time we can only predict that the next eruption will be in the year 2020 ± 2.

Key words: novae, cataclysmic variables – stars: individual (U Scorpii)

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Recurrent novae (RNe) are ordinary novae (binary systems with mass accreting onto a white dwarf until thermonuclear runaway is triggered) for which the recurrence timescale is between a decade and a century, such that more than one eruption has been observed (Payne-Gaposchkin 1964; Bode & Evans 2008; Evans et al. 2008). To have a fast recurrence timescale, the RNe must have a white dwarf near the Chandrasekhar mass and have a high accretion rate. These properties, at face value, imply that the white dwarf will soon exceed the Chandrasekhar mass and become a Type Ia supernova, and thus RNe are one of the premier candidates for the progenitor class of these supernovae. RNe typically have relatively fast eruptions, high ejection velocities, and small eruption amplitudes when compared to ordinary novae. Only 10 RNe are known with certainty in the Milky Way (Schaefer 2010).

U Scorpii (U Sco) previously erupted in 1999 March with a peak at $V = 7.5$ mag (Schaefer 2010). In quiescence, it has $V \approx 17.6$ and has deep *total* eclipses taking it down to $V = 18.9$ mag (Schaefer 2010) with an orbital period of 1.23 days (Schaefer 1990; Schaefer & Ringwald 1995). U Sco is the fastest of all known novae, fading by 3 mag from peak in just 2.6 days, while its rise from minimum to peak is 6–12 hr (Schaefer 2010). No light echo was detected to deep limits after the 1987 eruption (Schaefer 1988).

U Sco has now had 10 known eruptions, which occurred in the years 1863, 1906, 1917, 1936, 1945, 1969, 1979, 1987, 1999 (Schaefer 2010), and now 2010 as we report in this paper. With the discovery of the 1917, 1945, and 1969 eruptions (Schaefer 2001, 2004), it has become apparent that U Sco has had outbursts at intervals of 10 ± 2 years since 1900. The exceptions to this are the two intervals of 19 and 24 years, which are easily interpreted as being double intervals, with eruptions around 1927 and 1957 having been missed. (U Sco is $3\overset{\circ}{.}6$ from the Sun on every November 28, so a significant fraction of its very fast eruptions must be missed.) With this, it became apparent that the next eruption of U Sco should occur in the year 2009 ± 2. Schaefer (2005) made a better prediction, on the physical basis that the time between eruptions scales as the inverse of the average mass accretion rate between eruptions (as measured from the *B*-band flux), with the scaling determined by the inter-eruption light curves from prior eruptions. The predicted eruption date was 2009.3 ± 1.0. This is the first time that a specific star has been predicted to have an eruption on a specific date.

With this advance notice, a large international collaboration was formed to provide detailed photometry and spectroscopy in the X-ray, ultraviolet, optical, and infrared bands. With U Sco going from quiescence to peak to 1 mag below peak in 24 hr, we realized that we must have frequent monitoring of U Sco to get a fast alert of an eruption. To this end, we mobilized daily and hourly photometry with the SMARTS 1.3 m telescope in Chile, the fully robotic 2.0 m Liverpool telescope (Steele et al. 2004) in the Canary Islands, and the four ROTSE 0.45 m telescopes in Australia, Texas, Namibia, and Turkey. In addition, we mobilized a large number of observers through the American Association of Variable Star Observers (AAVSO). For the seven months each year centered on the opposition of U Sco, we got hourly data. The headquarters of the AAVSO served as the international clearinghouse for discovery reports and delivery of alerts to the world. In addition, U Sco was heavily monitored

Table 1
U Sco Pre-eruption Light Curve

HJD	Band	Magnitude	Source	Phase	Year
2451702.1932	CV	18.1 ± 0.1	AAVSO (LAQ)	0.038	2000.432
2451708.1195	CV	18.6 ± 0.1	AAVSO (LAQ)	0.854	2000.448
2451719.0413	CV	18.8 ± 0.1	AAVSO (LAQ)	0.729	2000.478
2452016.8446	V	17.90 ± 0.01	McDonald 2.1 m	0.738	2001.293
2452018.8356	V	18.05 ± 0.02	McDonald 2.1 m	0.356	2001.299
...					
2455223.9232	CV	18.6 ± 0.1	AAVSO (MJLE)	0.960	2010.074
2455223.9473	V	18.2 ± 0.1	AAVSO (HBB)	0.980	2010.074
2455224.1271	Visual	>16.5 ± 0.1	AAVSO(LMK)	0.126	2010.074
2455224.1649	V	>15.0 ± 0.1	ASAS-3N	0.156	2010.074
2455224.3438	CV	>9.2 ± 0.10	VSLOJ(Wny)	0.302	2010.075
2455224.9385	V	7.85 ± 0.10	AAVSO(HBB)	0.785	2010.076
2455224.9720	Visual	8.1 ± 0.3	AAVSO(SCK)	0.812	2010.077
2455224.9751	V	7.98 ± 0.01	AAVSO(DKS)	0.815	2010.077

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

from 2001 to 2009 with long time series photometry, where the main goal was to precisely measure the timing of the eclipses. The result of all this activity from 2000 to 2010 is the all-time best pre-eruption light curve for any nova. This paper presents all the magnitudes and an analysis of this large data set.

2. THE OBSERVATIONS

This paper reports on large data sets from diverse sources, with these being described in this section in chronological order for the start of the data sets. The first data set starts in 2001 and consists of many time series from Cerro Tololo and the McDonald Observatory, with some *UBVRI* measures but mainly centered on eclipses. The next three data sets started in early 2008 (frequent monitoring with the SMARTS 1.3 m telescope on Cerro Tololo, the four ROTSE telescopes, and the many visual observers of the AAVSO) to provide worldwide hourly coverage designed to make a fast discovery of eruption. The fifth data set starts in early 2009 with regular monitoring in four colors with the 2.0 m Liverpool telescope. In the last two months of 2009, we organized a special campaign with AAVSO observers to fill the solar gap, including the use of the *SOHO* satellite near the time of conjunction. In 2010 January, U Sco was monitored by many visual observers and with CCD imaging, with this providing the key pre-eruption and discovery observations. All of our observations are explicitly tabulated in Table 1.

Since 1987, one of us (B.E.S.) has heavily monitored U Sco, with emphasis on the light curve around the time of the eclipses (Schaefer 1990, 2005, 2010; Schaefer & Ringwald 1995). These observations have been made with the McDonald 2.7 m, 2.1 m, and 0.8 m telescopes in Texas as well as with the 1.3 m, 1.0 m, and 0.9 m telescopes on Cerro Tololo in Chile. The typical integration times were 300 s in the B and I bands and 100 s in the V band. Normal processing was carried out and the photometry was done using the IRAF package PHOT, which performs aperture photometry on the stars in this uncrowded field. The magnitude of U Sco was determined relative to a selection of nearby comparison stars for which the primary comparison star, named "COMP" (J2000 16:22:25.6 −17:51:34), has $B = 16.96$, $V = 15.87$, $R = 15.25$, and $I = 14.59$ (Schaefer 2010). The photon statistics, as calculated by PHOT, are generally smaller than 0.01 mag, but the systematic uncertainties, as represented by the scatter in the measures of standard star magnitudes (Landolt 1992, 2009), are typically 0.015 mag. The quoted uncertainty is the addition in quadrature of 0.015 mag and the uncertainty from photon statistics. For 2001 to 2009, this data set consists of 1983 magnitudes, mostly as fast time series photometry centered on times of eclipses. The specific analysis of the eclipse shapes has already been presented in Schaefer (2010), while a specific analysis of the eclipse times is reserved for a separate paper. For the study in this paper, the eclipse effects would only hide the other variability, so we have not included any magnitudes with an orbital phase between −0.10 and +0.10. In all, we have 162 magnitudes in the U, B, V, R, and I filters from 2001 to 2006.

Starting in early 2008, we (B.E.S., A.P., and L.X.) began frequent regular monitoring of U Sco with the 1.3 m SMARTS telescope on Cerro Tololo. This telescope is queue-scheduled, so an operator takes images of U Sco for us several times a week, thus allowing long-term frequent monitoring without requiring us to be at the telescope year-round. Most of the observations were 300 s exposures in the B band, but we also made several sets of nearly simultaneous *BVRI* images. The procedures and analyses were identical to those described in the previous paragraph. In all, we have 145 magnitudes from early 2008 until late 2009.

Beginning in early 2008, one of us (B.E.S.) started using the robotic ROTSE telescopes to monitor U Sco once every hour. The ROTSE telescopes (Akerlof et al. 2003) are four automated 0.45 m f/1.9 telescopes with 1°.85 fields designed to provide a very fast response to satellite triggers on gamma-ray bursts. The four telescopes are located at Coonabarabran, Australia; Mount Gamsberg, Namibia; Bakirlitepe, Turkey; and the McDonald Observatory, Texas. This wide coverage in longitude gives the potential for complete time coverage. No filters were used, so the resultant magnitudes are similar to a very broad R band. The exposure time was 60 s in all cases. The requested cadence was one exposure every hour from every ROTSE telescope, but problems such as clouds, dawn, daylight, a nearby Full Moon, an altitude lower than 20°, higher priority alerts for gamma-ray bursts, and the usual equipment problems all make for a substantially lower cadence. In the months around opposition, the ROTSE system achieved the ideal of nearly hourly coverage for around a quarter of the days, while the average coverage was roughly 15 images in every 24 hr interval. In the months approaching the conjunction of U Sco with the Sun, the daily coverage decreased to one or two images per 24 hr interval. For example, in 2009, ROTSE first recorded that U Sco was not in eruption on January 9 (43 days after conjunction) and last imaged U Sco on October 18 (40 days before conjunction). The limiting magnitude varied widely (with clouds, altitude, focus, and the Moon), yet U Sco was visible at low significance on about half of the images. Even on the best images, U Sco did not get better than a 5σ detection, so in no case do we have accurate photometry from ROTSE. In all, we have a set of roughly 7000 usable U Sco images from ROTSE. One of the goals of the hourly monitoring by ROTSE was so that we (B.E.S., A.P., and M.T.) could frequently check the images to try to discover the eruption as soon as possible. Another goal was to catch any pre-eruption rise (see Section 4) even if the amplitude was small and the duration was short. For the eruption in 2010 January, there was no significant pre-eruption rise and our (B.G.H., S.D., J.M., and M.L.) small-telescope monitoring produced a better light curve than ROTSE. A third reason for the ROTSE program was the hope that we would catch U Sco on the rise. In all previous eruptions, U Sco has been recorded on the rise only three times, each being close to the peak, with the rise from quiescence apparently lasting 6–12 hr (Schaefer 2010). In the hours before the discovery of the 2010 eruption, the Namibia ROTSE telescope did not look at U Sco due to a higher priority follow up to a gamma-ray burst, the Turkey ROTSE had clouds, and the Australia ROTSE was down with equipment problems. With the chance lack of any data on the rise and the poor photometric accuracy of the two years of monitoring, we are not presenting any of the ROTSE magnitudes in this paper.

Beginning in early 2008, we (M.T. and A.A.H.) organized a steady watch on U Sco by the many observers of the AAVSO. The primary goal was to catch U Sco's eruption as quickly as possible. The widespread distribution in longitude of the many AAVSO observers makes for frequent monitoring, and this was the best chance of catching the eruption early. For the half-year around opposition, U Sco was checked for outburst up to 6.7 times per day for monthly averages. A further requirement for getting fast reactions from the world's telescopes was that the discovery had to be communicated from the discoverer to the rest of the world. For this vital need, the AAVSO Headquarters served as an around-the-clock, every-day-of-the-year communication center. Observers were instructed to report their discovery electronically, then automated services would alert key individuals who would test for validity and solicit fast confirmation. Once the eruption was discovered, we would immediately start notifying the world through IAU Circulars and long-prepared phone and email lists. In the actual eruption, this system worked perfectly.

As part of this effort, many AAVSO members made positive measures of the brightness of U Sco during the pre-eruption phase. The AAVSO database contains 412 magnitudes (from 29 observers) and 2853 limits (from 102 observers) between the end of the 1999 eruption and the start of the 2010 eruption (JD 2451557.148 to 2455224.127). The limits were vital at the time of the observation for knowing that U Sco had not erupted, but now they are not helpful for following the accretion rate. A further 77 magnitudes are not used here, primarily because the photometric system is not standard and the meaning of the magnitude would be unclear. This leaves us with 335 positive detections in the pre-eruption time interval. Just over 90% of these magnitudes were made with unfiltered CCD imaging, where the magnitudes were calibrated differentially from nearby comparison stars using either the *V*-band or the *R*-band magnitudes. These magnitudes (designated CV or CR) will not be exactly on either the *V* or the *R* magnitude systems, but the expected deviations (less than 0.1 mag) are always small compared to normal variations of U Sco. Our instrumentation is a 16 inch f/10 Schmidt–Cassegrain with a *V* filter located in New Smyrna Beach, Florida (B.G.H.), an 18 inch Newtonian telescope without filter located in Barnesville, Maryland (J.M.), and a 10 inch Schmidt–Cassegrain telescope with a *V* filter located in Clermont, Florida (S.D.). During the critical month before the eruption, all positive detections in the AAVSO database are provided by us (B.G.H. and J.M.) from CCD images.

Beginning in early 2009, we (M.J.D. and M.F.B.) started monitoring U Sco with the robotic 2.0 m Liverpool telescope (Steele et al. 2004) at the Observatorio del Roque de Los Muchachos on La Palma in the Canary Islands. The goals were to define the pre-eruption light curve in many bandpasses and perhaps to catch a pre-eruption rise or the eruption rise itself. The photometry was all differential with respect to the comparison stars given in Schaefer (2010). The images were usually taken through many filters in quick succession once each night. The filters we used were the *B*, *V*, Sloan r', and Sloan i'. Each light curve point consisted of three 60 s exposures. The data were analyzed using Starlink software. The typical photometric errors had an uncertainty of 0.01–0.02 mag. In all, we present here 173 magnitudes from the Liverpool telescope.

An important practical question was whether U Sco erupted during its yearly conjunction with the Sun every November 28. The worst-case scenario would be for U Sco to go up in early November, fade back to its quiescent level before any detection was made, and for the eruption to be completely missed. If U Sco went up while behind the Sun, it would be vital to know this so that our community would not be waiting anxiously with many resources, and also so that observations in the late tail could still be performed. For this, deep images would have to be made as far into twilight as possible. Professional telescopes do not go low enough in the sky, so the push into twilight was made entirely by AAVSO observers. For the 2008 November solar conjunction, U Sco was lost on November 2 and deep images showed U Sco to be near quiescence ($V > 16.1$) on January 3, for a solar gap of 62 days. For the 2009 November solar conjunction, U Sco was last detected at $V = 18.6$ on October 21 (J.M.), was fainter than 12.0 mag on November 4 (M.L.), last checked on November 6, while after conjunction our images showed it to be fainter than $V = 14.0$ on December 27 (M.L.), fainter than $V = 14.3$ on December 28 (M.L.), fainter than $V = 17.4$ on December 30 (B.G.H.), and at quiescence ($V = 17.6$) on January 4 (B.G.H.), for a solar gap of 51–59 days. From the *V*-band light curve template (Schaefer 2010; Schaefer et al. 2010b), U Sco is at $V = 16.6$ ~42 days after the peak. With this extremely short duration, the possibility for a missed eruption was for a peak from 2008 November 3 to 23 or from 2009 November 7 to 16. As a chance to discover a U Sco eruption in the week around solar conjunction, one of us (S.D.) used the *SOHO* LASCO C3 instrument (which hides the Sun behind a white light coronagraph and produces images of stars, comets, and the corona out to 32 solar radii from the Sun) to demonstrate that the nova never came to peak (i.e., $V > 8.6$ mag) during that week-long interval.

The last positive detection of U Sco before its eruption was by B.G.H. on JD 2455223.9473. Nevertheless, there were later

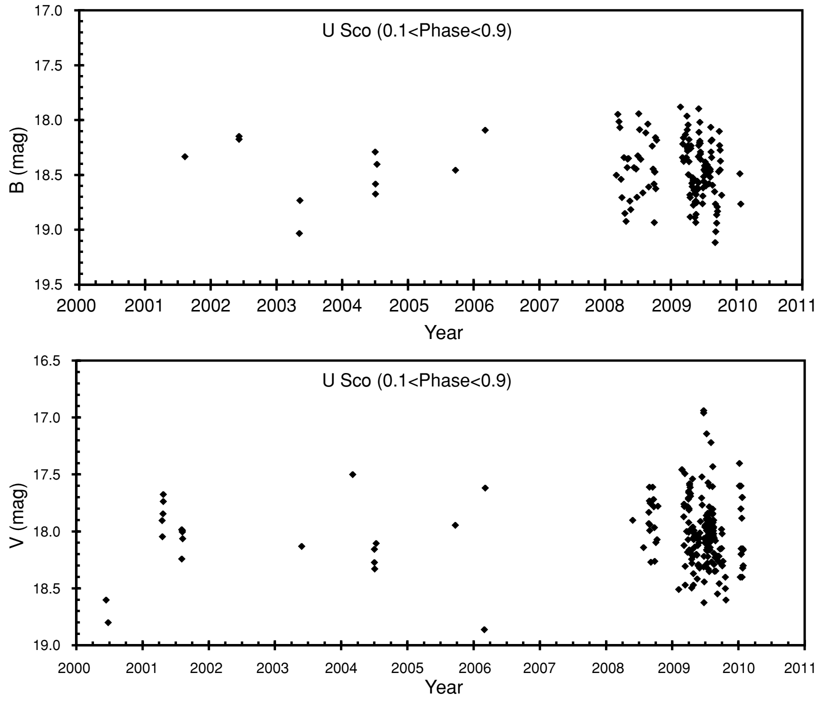

Figure 1. U Sco light curve in *B* and *V*, from 2000 to 2010. The *B*-band light comes almost entirely from the disk and is a measure of the mass accretion rate. This light curve does not include observations within 0.1 phase of the eclipses. The light curves show substantial short-term changes but no significant long-term variations. Table 1 contains roughly twice as many displayed magnitudes for the *R* and *I* bands, while we have 1983 additional magnitudes from eclipse time series from 2001 to 2009.

useful upper limits. Observing from the island of Hawaii, M.L. used a 20 inch f/3.6 reflector to place a visual limit of >16.5 mag on JD 2455224.1271. The ASAS-3N telescope took a *V*-band image with a 180 s exposure on JD 2455224.1649 and we (G.P., D.M.S., and B.P.) did not detect any source to a limit of 15.0 mag. This robotic telescope is located at Maui in Hawaii at an elevation of 3056 m, with an f/2.0 lens with a focal length of 200 mm for a field of view of 8°.5 on a side on a 2048 × 2048 pixel CCD chip. The last known observation before discovery (with $V > 9.2$) was taken by Y.W. on JD 2455224.3438 with a 60 mm f/5.9 refractor with an unfiltered CCD located in Yokosuka, Japan.

From these sources, we have collected 815 magnitudes for U Sco between the end of the 1999 eruption and the discovery of the 2010 eruption. (We also report on 16 useful limits, as described above.) These are presented in Table 1 for which the printed version includes only the first five lines and the last eight lines, and the online version presents all 831 magnitudes and limits. The first column lists the Heliocentric Julian Date (HJD) of the observation. The second column lists the band of the observation. The third column lists the magnitude and 1σ uncertainty. The fourth column lists the source of the magnitude, either by identifying the telescope or by giving the AAVSO or VSOLJ observer identification code. HBB is for B. G. Harris, DKS is for S. Dvorak, MJLE is for J. Menke, LMK is for M. Linnolt, SCK is for B. E. Schaefer, Wny is for Y. Watanabe, and LAQ is for A. Liu. The fifth column is the orbital phase of U Sco (with primary eclipses at phase 0.0 and 1.0 and secondary eclipses at phase 0.5) for the pre-eruption ephemeris of HJD = 2451234.539 + N × 1.2305470. The last column gives the fractional year corresponding to the Julian Date of the observation. Figure 1 displays the full light curve for the *B* and *V* filters, while Figure 2 shows the *B*- and *V*-band light curve after the start of 2009. Figure 3 shows the folded light curves for the *B* and *V* bands.

Table 2 lists various characteristic quantities (magnitudes, colors, and fluxes), their averages, their rms scatters, and the number of observations going into the averages. For the science of this paper, we are only interested in the non-eclipsing behavior, so to be conservative, we have included only measures more than 0.10 in phase (0.123 in days) away from the central eclipse times (i.e., between phases 0.10 and 0.90). For the colors, we have included only those colors derived from two magnitudes taken within 0.005 days of each other to keep the errors introduced by fast variations to a minimum. The overall magnitudes (for all bands) and colors for the entire time interval (from 2000 to the 2010 eruption) are recorded. We also break up the *B*- and *V*-band magnitudes into smaller intervals to seek significant variations. Finally, we include the average *B*-band fluxes as defined in Section 6.

3. DISCOVERY OF THE 2010 ERUPTION

The 2010 eruption was discovered by us (B.G.H. and S.D.) as part of systematic nightly monitoring aimed specifically at the discovery of the eruption. B.G.H. imaged U Sco at UT 28.4385 on 2010 January (JD 2455224.9385), then saw the bright star in the center of the field, then quickly realized that U Sco was in eruption, and then alerted the AAVSO. After a telephone alert from B.G.H., B.E.S. made direct visual confirmation of her discovery with a 6 inch telescope, sent out an IAU Circular (Schaefer et al. 2010a), and with A.P. and M.T. made alerts to our entire collaboration. Independently, Dvorak discovered the eruption, notified the AAVSO, and started a time series on U Sco to cover the short time interval until dawn got too bright to continue. These initial observations are included in Table 1. Circumstances, pictures, and anecdotes on the two independent discoveries are given in Simonsen & MacRobert (2010).

The discovery of the 2010 eruption was a fulfillment of the prediction in Schaefer (2005) that U Sco would next

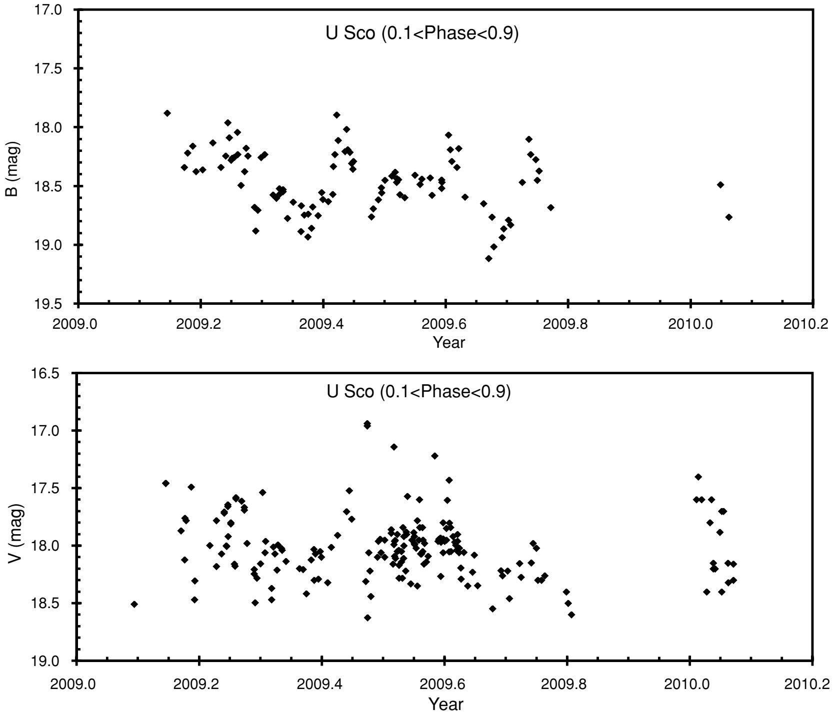

Figure 2. U Sco light curve in *B* and *V* for the last year before eruption. The observations within 0.1 phase of eclipses are not included so as to concentrate on changes of the system brightness alone. U Sco shows frequent short timescale variations, but long-term changes are apparently not significant. In particular, U Sco does not show any pre-eruption rise or dip on timescales from one day to years before the eruption.

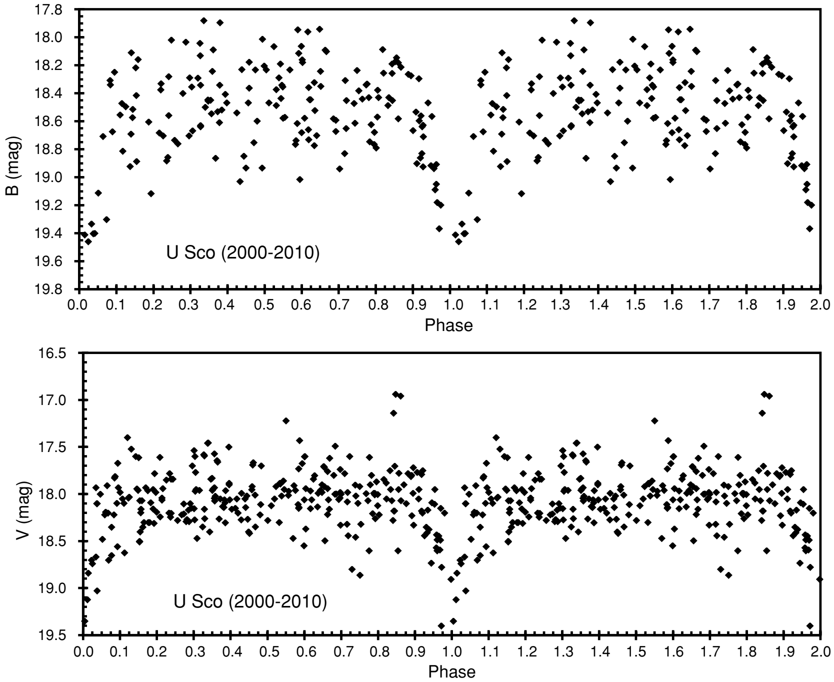

Figure 3. U Sco phased light curve in *B* and *V*. The two panels show the *B* and *V* magnitudes as a function of U Sco's orbital phase for all observations from 2000 until the 2010 eruption. Each magnitude is double plotted, once for phases 0–1 and a second time with unity added to the phase to ease the visibility of the eclipse. Both light curves show substantial short-term variations superposed on a flat light curve with eclipses. The eclipses look rather ragged, the result of taking one isolated point from many eclipses over which the system is varying up and down. (Time series through individual eclipses show a well-defined classic eclipse shape.) No secondary eclipse is visible in either *B* or *V*. Note that the scatter apparent outside of eclipse is much smaller during the eclipse, pointing to the flickering region being eclipsed.

erupt in the year 2009.3 ± 1.0. The eruption in 2010.1 falls well within the 1σ region of the prediction. This adds good confidence to the physical method of summing the total accreted material based on the *B*-band flux in the prior inter-eruption interval.

4. VARIATIONS IN THE LIGHT CURVE

The folded light curves (see Figure 3) show the primary eclipse at phases 0.0, 1.0, and 2.0. (The magnitudes are double plotted to make the eclipse at phase 1.0 easily visible.) The

Table 2
Average Magnitudes, Colors, and Fluxes

Quantity	Date Range	Average	rms	Number
U	2004.5	18.13	...	1
B	2001.6–2010.1	18.45	0.26	145
V	2000.4–2010.1	18.01	0.29	229
R	2001.2–2009.8	17.67	0.26	127
I	2001.5–2009.7	17.35	0.14	115
Sloan r'	2009.3–2010.1	17.86	0.18	26
Sloan i'	2009.1–2010.1	17.53	0.20	33
$U-B$	2004.5	−0.27	...	1
$B-V$	2005.7–2010.1	0.54	0.06	34
$V-R$	2001.2–2009.4	0.34	0.05	10
$R-I$	2004.4–2009.7	0.46	0.09	7
$r'-i'$	2009.3–2010.1	0.29	0.07	33
B	2001.6–2006.2	18.45	0.29	11
B	2008.1–2008.8	18.42	0.28	34
B	2009.1–2009.8	18.46	0.26	98
B	2010.0–2010.1	18.63	0.20	2
V	2000.4–2001.7	18.07	0.33	12
V	2003.4–2006.2	18.10	0.40	9
V	2008.3–2008.8	17.91	0.20	18
V	2009.1–2009.2	17.86	0.37	9
V	2009.2–2009.3	17.92	0.26	25
V	2009.3–2009.4	18.12	0.19	23
V	2009.4–2009.5	17.93	0.46	17
V	2009.5–2009.6	17.98	0.22	58
V	2009.6–2009.7	18.06	0.22	27
V	2009.7–2009.9	18.28	0.18	13
V	2010.0–2010.1	17.97	0.33	17
$F_{B,18}^{1.5}$	2001.6–2006.2	0.58	0.20	11
$F_{B,18}^{1.5}$	2008.1–2008.8	0.60	0.23	34
$F_{B,18}^{1.5}$	2009.1–2010.1	0.56	0.20	100
$F_{B,18}^{1.5}$	1999.2–2010.1	0.58	0.05[a]	145
$F_{B,18}^{1.5}$	1987.4–1992.2	0.50	0.03[a]	26
$F_{B,18}^{1.5}$	1979.5–1987.4	0.66	0.05[a]	4
$F_{B,18}^{1.5}$	1969.1–1979.5	0.55	0.12[a]	2
$F_{B,18}^{1.5}$	1954.5	0.33	...	1

Note. [a] The quoted value is not the rms scatter of the quantity, but rather is the 1σ uncertainty in the average value.

out-of-eclipse brightness varies substantially, and this makes for a ragged eclipse light curve because each point is from a different epoch eclipse with a different amount of flickering light added. The scatter around the middle of the eclipse is much smaller than the out-of-eclipse scatter, which implies that the flickering region is small and centrally located.

No secondary eclipse is visible in the B and V bands. However, in the I band, the secondary eclipse is visible with amplitude roughly 0.3 mag (see Figure 47 of Schaefer 2010). This is readily understood as the companion star is much cooler than the accretion disk, so eclipses of the companion can only become noticeable at longer wavelength.

All cataclysmic variables, including novae and RNe, show fast flickering. U Sco is no exception, and this flickering causes the substantial scatter in Figures 1 and 2. To quantify this, we have calculated the magnitude difference between pairs of magnitudes in the same band, with the pairs being separated in time by some range of delays. When the delays are shorter than one hour, the rms scatter of the magnitude differences is 0.06 mag, which is consistent with the expected scatter as based only on the quoted error bars. When the delays are longer than one day, the rms scatter of the magnitude differences is 0.27, which corresponds to no correlation between the flickers. The rms scatters are 0.09, 0.13, 0.18, 0.19, and 0.21 mag for delays of 0.05–0.10, 0.10–0.15, 0.15–0.20, 0.20–0.50, and 0.50–1.00 days, respectively. With this, the timescale for correlated variations is from one hour to one day. The amplitude of these variations is given by the maximum values of the magnitude differences, which is roughly 0.4 mag for all delays longer than 0.05 days. Our observations are not sensitive to fast, small-amplitude variations.

On timescales from days to a month, significant variations can be seen in Figure 2. For example, U Sco is systematically faint from 2009.30 to 2009.40, and then has a week-long "flare" with a factor of 2 brightness increase centered on 2009.43. These variations are most prominent in the B band.

Many of the RNe have large secular variations in their quiescent light curves (Schaefer 2010). However, U Sco does not appear to have any variations over the last decade, as can be seen in Figure 1. To quantify this for the B and V light curves, Table 2 gives the averages for various time intervals. Again, no significant variations on timescales of one year or longer are found, even with small error bars due to the many magnitudes included in the averages.

On longer timescales, U Sco has small, marginally significant variations. During the last four inter-eruption intervals, the average B magnitude was 18.44 ± 0.07, 18.30 ± 0.05, 18.52 ± 0.04, and 18.45 ± 0.02 for 1969–1979, 1979–1987, 1987–1999 (Schaefer 2005), and 1999–2010, respectively. The χ^2 for the observed averages (on the hypothesis that the average is a constant) is 12.1 for 3 degrees of freedom. The best argument for the significance of these variations is that the deviations from the average are correlated with the duration of each inter-eruption time interval as predicted by theory (see Section 7).

The earliest recorded image of U Sco in quiescence is from the original Palomar Sky Survey. We measure $B = 18.80 \pm 0.15$ and $R = 18.00 \pm 0.18$ for 1954 June 29. This is substantially fainter than is normal for later decades, and the time is far from any plausible eclipse.

In all, U Sco displays moderate variations on all timescales from one hour up to half a century. The typical (out-of-eclipse) amplitude of variation is 0.4 mag, with the extreme observed range of $18.9 > B > 17.9$. With the blue light from U Sco being dominated by the accretion disk, these variations record the changes in the accretion rate off the companion star.

5. NO PRE-ERUPTION RISE OR DIP

Robinson (1975) examined all known pre-eruption light curves of novae as based on reports in the literature. He found that 5 out of 11 novae have pre-eruption rises, lasting months to years in advance of the eruption, with amplitudes from 0.15 to 1.5 mag. Collazzi et al. (2009) used the original archival photographic plates to measure many pre-eruption light curves, including the key novae with claimed pre-eruption rises. Four of the five claimed pre-eruption rises were found not to exist as based on our examination of the original plates, such that the claimed rises were caused by simple errors in the literature. Nevertheless, one of the rises (for V533 Her) was confirmed and extended, with the rise being an exponential increase over ~1.5 years and a brightening by up to 1.5 mag. Also, an additional pre-eruption rise was confirmed in V1500 Cyg, which brightened from roughly 21.5 mag to roughly 13 mag in the month preceding the eruption. (V1500 Cyg had the fastest known *classical* nova eruption, and was second only to U Sco itself amongst all novae.) In addition, a complex pre-eruption dip was confirmed for the RN T CrB in the year before the eruption, with the dip being 1–2 mag deep. In all, 3 out of 22 novae had either pre-eruption rises or pre-eruption dips.

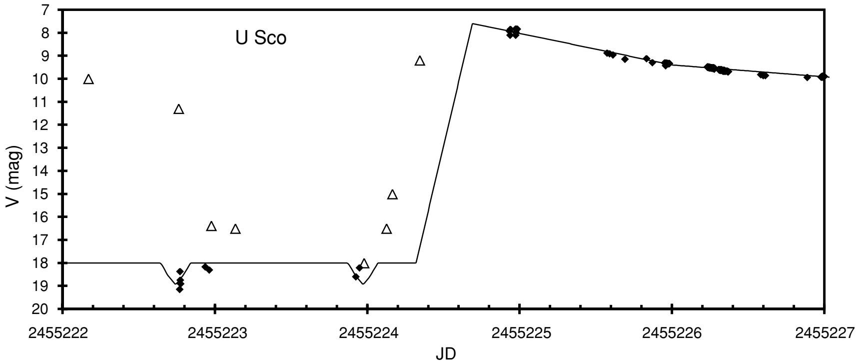

Figure 4. Rise to peak. The line shows our best idealized light curve, with the eclipses during quiescence, no pre-eruption rise or dip, the typical fast rise to the peak (taken to be the same as in 1999) and the exceptionally fast decline of this RNe. The limits are depicted by empty triangles, where additional limits are taken from the AAVSO database. Several observations have been converted to the V band with the colors from Table 2.

With other RNe and the fastest classical nova having anticipatory rises and dips, we should investigate whether U Sco has any similar changes. (We were also hopeful that any such phenomenon would allow us to anticipate the next eruption.) For this, we can use our light curves to seek any rises or dips. A glance at Figure 1 quickly shows that there is no significant rise or dip. Quantitatively, Table 2 shows that the B and V magnitudes from 2010.0 to 2010.1 are not significantly high or low. And looking at the bottom of Table 1, we see that the last positive detection of U Sco has $V = 18.2$ (B.G.H.) just 24 hr before the discovery. With this, we can put strong limits on the presence of any pre-eruption rise or dip to be less than roughly 0.2 mag in amplitude on timescales from one day up to a year.

6. THE RISE TO PEAK

U Sco rises from quiescence to peak in roughly 6–12 hr, although this is based on just three pre-peak positive detections and one limit (Schaefer 2010). For the 1936 eruption, a single Harvard plate shows $B = 10.75$ at a time 0.25 days before peak. For the 1987 eruption, Dr. N. W. Taylor measured $V = 14.0$ in the day before the peak. For the 1999 eruption, P. Schmeer measured $V = 9.5$ at a time 0.31 days before the peak. The final rise to maximum is at a rate of around 19 mag per day, which would imply a rise time of roughly 12 hr if the rise is uniform throughout. For the 1999 eruption, B. Monard sets a limit that $V > 14.3$ at a time 0.46 days before the peak.

We can use our data to obtain the best estimate for the time of peak in the 2010 eruption. The discovery image was taken at JD 2455224.9385 (B.G.H.), and we have measured the magnitude of U Sco (with respect to the comparison star sequence in Schaefer 2010) to be $V = 7.85$ with the systematic uncertainties dominating at around 0.10 mag. The observed initial rate of decline is 1.4 mag per day (Schaefer et al. 2010b). The peak magnitude of U Sco is $V = 7.5$, primarily as based on the observed peak of the 1999 eruption (Schaefer 2010). In an exhaustive comparison of all RN eruptions and those from U Sco in particular, Schaefer (2010) found that all RNe are consistent with having identical eruption light curve shapes, and this is our basis for taking the peak from the 1999 U Sco eruption as being the same for the 2010 eruption. With this, the peak of the 2010 eruption would have been 0.25 days before discovery, which gives a peak at JD 2455224.69 with a likely uncertainty of 0.07 days.

The observational limits from the 2010 eruption show that the eruption could not have started much before the ASAS-3N image at JD 2455224.1649. From the limits on the prior eruptions, the eruption started 0.25–0.5 days before the peak, which is roughly from JD 2455224.19 to 2455224.44. Thus, the time of the start of the expansion, as required by the "universal decline law" of Hachisu & Kato (2006), can be expressed as JD 2455224.32 ± 0.12. The observations and our best idealized model for the rise to peak are presented in Figure 4.

Disappointingly, we have no observations from JD 2455224.3438 to 2455224.9385 and thus have completely missed the entire rise and the hour of peak. In January, U Sco is fairly close to the Sun and hence only visible from a narrow slice of longitude at any given time. In the southern hemisphere, the start of the rise would only have been visible from the longitudes in the Indian Ocean, while the peak would only have been visible from the longitudes in the South Atlantic Ocean.

7. PREDICTING THE NEXT ERUPTION

Schaefer (2005) presented a new method for predicting the date of the next eruption of an RN based on the requirement that some constant amount of mass must be accumulated by the white dwarf between eruptions. Accretion rates vary substantially (Schaefer 2010, and see Figure 1), so the interval between eruptions (T) depends on the average accretion during that time. If the accretion rate is high then the interval will be short, while if the accretion rate is low then T will be high. For U Sco, the blue light is dominated by the accretion disk, so the blue flux (F_B) will be a measure of the accretion rate. In particular for U Sco, the accretion rate will be proportional to $F_B^{1.5}$ (Schaefer 2005). By averaging $F_B^{1.5}$ over each interval T, we can derive a quantity that is proportional to the average accretion rate. Then, $\langle F_B^{1.5}\rangle T$ should be proportional to the total mass accreted between eruptions, which should be a constant. Schaefer (2005) found that this quantity is indeed constant for four intervals for T Pyx and three intervals for U Sco (despite widely varying values of T for each system), with this providing a good test of nova trigger theory. These *observed* values for $\langle F_B^{1.5}\rangle T$ provide empirical measures of the mass required to trigger the eruptions. Then, based on the observed B magnitudes up until 2005, Schaefer (2005) was able to predict that U Sco would next erupt in 2009.3 ± 1.0. Schaefer (2010) updated the situation to arrive at the same predicted date. As noted above, the actual eruption on 2010.1 falls well within this prediction.

Now, with the full pre-eruption light curve, we can better test the prediction and can refine the constant for use in predicting the next eruption. To this end, we have first converted the B-band magnitudes to flux units where $B = 18$ is taken to be the unit flux ($F_{B,18}$), which equals $10^{(18-B)/2.5}$. The accretion rate will then be proportional to $F^{1.5}_{B,18}$. To get the time-averaged value from 1999.2 to 2010.1, we should not simply average all the values, as this would produce a high weight to the behavior of U Sco during 2008 and 2009 (during which the majority of the B-band magnitudes were taken). Instead, we have taken time intervals and combined them with weights given by their duration. In Table 2, we list the average values of the measured $F^{1.5}_{B,18}$ for three intervals with roughly constant frequency of observations. The uncertainty in these averages is the rms scatter divided by the square root of the number of observations. The durations of these intervals were then used as weights for averaging the intervals, and the uncertainty in the overall average comes from the usual propagation of errors. The resultant average over the entire interval between the 1999.2 and 2010.1 eruption is listed in Table 2. In all, $\langle F^{1.5}_{B,18}\rangle = 0.577 \pm 0.045$.

Schaefer (2005) produces values of $\langle F^{1.5}_{B}\rangle$ for the three prior inter-eruption intervals. These need to be updated for four reasons. First, we need to standardize to the same flux level (i.e., $B = 18$) as the unit flux. Second, we should be consistent and not include any magnitudes within phase 0.10 of the eclipse. Third, the individual observations should be formed into the averages with equal weight (instead of weighted by the measurement uncertainty) because intrinsic fluctuations are substantially larger than the measurement errors (so we would not want to give high weight to a bright point simply because it has a small error bar). Fourth, the 1969–1979 interval has only two magnitudes, so instead of determining the uncertainty based on the rms scatter of just these two, we have equated the scatter to that during the 1987–1999 interval. The resultant $\langle F^{1.5}_{B,18}\rangle$ values are given in Table 2.

U Sco erupted in the years 1969, 1979, 1987, 1999, and 2010, with T values of 10.4, 7.9, 11.8, and 10.9 years for the four inter-eruption intervals. The longest interval is a factor of 1.5 times the shortest interval. We see that the shortest interval has the highest average accretion rate, while the longest interval has the lowest average accretion rate, and the two middle intervals have the middle average accretion rates. The four intervals in time order have $\langle F^{1.5}_{B,18}\rangle T$ values of 5.7 ± 1.2, 5.2 ± 0.4, 6.0 ± 0.4, and 6.3 ± 0.5. (The weighted average of these four values is 5.77 ± 0.24.) Nova trigger theory predicts that these values should be a constant. Indeed, the χ^2 equals 3.4 for the hypothesis that the four values are equal to a constant, which is acceptable given the 3 degrees of freedom, and we see that the values are consistent with being a constant despite T varying by up to a factor of 1.5. Thus we have an improved confirmation of nova trigger theory.

U Sco erupted in 1945 and 1969, with an inter-eruption interval of 23.7 years. The long interval could be because *one* eruption was missed around 1957 (with intervals of around 11.8 and 11.9 years) or because *two* eruptions were missed around 1953 and 1961 (with intervals of around 7.9, 7.9, and 7.9 years). These two possibilities can be distinguished due to their greatly different prediction as to the quiescent B magnitude, roughly 18.52 versus 18.30, respectively. The one measured magnitude ($B = 18.80 \pm 0.15$ from 1954.5) suggests that the accretion rate was low, and hence that there was only one missed eruption.

When will the next eruption of U Sco occur? Over the next decade, we can keep track of the B-band magnitudes and work out when $\langle F^{1.5}_{B,18}\rangle T$ will equal 5.77 ± 0.24. Such a prediction will only be accurate to roughly 5 months out of 10 years, which is fairly good. However, this method cannot be used yet, because we cannot predict the variations in the U Sco accretion rate. For now, the best that we can do is to use the long record of U Sco where all of its inter-eruption intervals are 10 ± 2 years. With this, we predict the next U Sco eruption to be in 2020 ± 2.

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