Summary of 2010 U Sco nova observing campaign

Brad Schaefer, July 1, 2010

A. NEW PHENOMENA DISCOVERED:

1. Early Flares (no known explanation)

During Days 8-15, U Sco shows occassional flares with amplitude 0.5 mag and rise-or-fall times of 0.6-1.2 hours. These flares were been first pointed out by Worters et al. (IAUCirc 9114) and Munari et al. (IBVS 5930), with Richards, Allen, and Stockdale providing exquisite fast photometry of many examples. Such fast flares have never been seen in any previous nova, so this is a newly discovered phenomenon. The only reason for this discovery is because we have an awesome coverage (23,000 magnitudes averaging one every 4 minutes throughout the entire eruption!), whereas all previous observations have only had a few novae with only a few hours of fast photometry, and this prior coverage is completely inadequate to discover occassional flares in a restricted time interval.
The early flares are *not* associated with the usual flickering in CVs. The reason that we can be certain of this is because the inner binary system (where any of the usual flickering in disks would occur) is completely shrouded by outlying material (mainly from the SSS wind). We know this positively for two reasons; first the eclipses are not visible (they start suddenly around Day 15 when the shroud lifts) so the inner binary must still be covered, and second that the supersoft X-ray source

is completely invisible (with the SSS suddenly appearing from Days 12-14). So the early flares must be associated with the shell or the outer SSS wind.

OK, so what can cause the early flares? The rise/fall time proves that the size of the optical emitting region must be smaller than 0.6-1.2 light hours in size, and since the ejecta is not relativistic, the real size must be greatly smaller than this limit. On day 10, the expanding shell (at velocities of 5000 km/s) is 4 light-hours in size. So the emitting region can only be a miniscule fraction of the whole shell. With a flare amplitude of 0.5 mag, the flare emitting region is giving off just a little less than the light being given off by the entire rest of the shell. The fast fall time implies that the 'hot' mass must have a relatively small mass so that it can cool fast enough. So the picture we have is a very small mass suddenly appearing, flaring, cooling fast, and fading away. I have no idea where this hot blob comes from, what powers it, or why it appears suddenly.

I wonder how these early flares relate to the large-amplitude long-duration 'jitters' seen in many classical novae (e.g., DK Lac, HR Del, V723 Cas). These 'jitter' novae have been made into an independent class, with many of their properties measured (Strope, Schaefer, & Henden 2010, AJ, in press, arXiv:1004.3698). U Sco apparently has a very smooth light curve, but maybe there is a continuum of jitter sizes, for which we are now just seeing the small amplitude end (solely because only U Sco has the exhaustive coverage that would reveal such). An argument against this idea is that in U Sco we only see the flares only around the transition region (Days 9-15), whereas the jitters are always seen from the time of peak up until the start-or-end of the transition region. The only way to advance on this question is to get great coverage by fast photometry of many other novae.

The literature has no explanation for the large-amplitude blatant jitters that are long-known. And I have no real idea as to the cause of the early flares on U Sco. Both of these phenomena are calling out for a theoretical explanation.

2. Optical Dips (caused by raised rims of proto-disk)

For Days 41-61, the out-of-eclipse light curve shows deep dips, with typical depth 0.5-0.7 mag and typical duration 0.2 in phase. These dips occur at any phase from 0.25-0.85, they show no apparent correlation with orbital phase, and they do not recur from orbit-to-orbit. The 'shape' of the dips are generally 'V-shaped'. These are big dips, highly significant, and seen by multiple observers. There is zero precedent for anything like this from novae at any time (for the simple reason that no one has ever looked well enough in the past).

I have a simple explanation for this new phenomenon. The optical light comes primarily from a small region centered on the white dwarf (as proved by the primary eclipses being deeper than 1.0 mag and being centered close to the time of conjunction). The dips all start and stop near the regular out-of-eclipse level, so the dips can only be caused by eclipses of the central light source. To produce eclipses at phases 0.25-0.85, the eclipsing bodies can only be spread completely around the white dwarf. I can show from the eclipse mapping (see the next section) that the optical light arises from a central-bright disk, so we know that the disk is present and spread around the WD, providing a source of occulters. We also know the inclination of the U Sco orbit (either ~80 degrees [Hachisu et al.] or 82.7+-2.9 degrees [Thoroughgood et al.]), so the line of sight to the central source is just skimming above the top of the accretion disk. We also know that accretion disks will have raised rims, caused by impacts of the accretion stream at various positions. So it is easy to put these components together. In the chaos as the accretion stream collides with itself and the disk, the disk will have transient raised rims and these will necessarily occult the bright inner regions, with the total optical light dipping. This is a simple explanation using only well-known components.

Indeed, there is a well-known closely analogous case - the X-ray dippers. Many LMXRBs with inclination around 80 degrees show X-ray dips. The X-ray dips are transient with variable duration. The X-ray dips are certainly caused by 'raised rims' in the accretion disk. While there are diferences (NS vs. WD, a very small X-ray source near the NS versus a larger optical source from the inner edge of the disk), the similarities are close and striking. So the X-ray dips provide a strong precedent and analogy for the optical dips.

B. ECLIPSE MAPPING

1. Days 15-26; Uniform Spherical Source w/ Radius 4.1 Rsun

The eclipses start suddenly on Day 15 or just before, with the amplitude going from 0.6 mag to 0.8 mag from Day 15 to Day 26. We have excellent light curves. I have performed 'eclipse mapping', with models of uniform disks, multiple disks, coronae of various types, Gaussian and exponential light sources, and disks with arbitrary power law radial distribution of surface brightness. Of all these models, the best fit is the simplest model, a uniform sharp-edged disk centered on the WD. The radius in the first days is 4.1 Rsun. The interpretation is easy, as the optical source is from emission by the spherical wind being driven off the WD by the continuing nuclear burning near the WD surface.

The out-of-eclipse light shows a highly significant asymmetry with the brightness around phase 0.25 being just over 0.1 mag brighter than around phase 0.75. Such an asymmetry can only occur if there is mass away from the axis joining the centers of the stars. The only real possibility for this is with material off to one side near the outer edge of the accretion disk. This is easily interpreted as being the re-formed accretion stream, where the inner edge of the stream is illuminated by the SSS and is bright when viewed from Earth around phase 0.25. This asymmetry was apparent as soon as the binary becomes visible on Day 15, so the accretion stream has already formed by this time.

2. Days 26-41; Rim-Bright Disk w/ Radius 3.4 Rsun

Around Day 26, the shape of the primary eclipse changes. A simple analysis proves that all of the optical light is now coming from near the orbital plane. All light sources with radial symmetry fail by a lot. Disk sources with the light either centrally bright or uniform in surface brightness all fail by a lot. The only model that fits well is a rim-bright disk of radius 3.4 Rsun.
So the nova wind has turned dim. Also, this shows the appearance of the proto-disk. [Actually, the first of the normal flickering associated with the accretion disk occurs on Day 24.5] The bright rim is caused by some combination of the raised rims scattering more light and the lack of material in the inner part of the disk (because viscocity has not yet had a chance to fill up this region). The lack of a small-bright-inner light source explains why the raised rims of the proto-disk have nothing to eclipse to create optical dips.

3. Days 41-67; Center-Bright Disk w/ Radius 2.2 Rsun (quiescence)

The shape of the primary eclipse again changes. The eclipse mapping shows a source concentrated near the orbital plane, best fit by a centrally-bright disk of radius 2.2 Rsun. (Some egresses show 'wings' on the eclipses so that there must be some extra light outside this radius towards the position of the accretion stream.) This configuration is indentical to the quiescent configuration, so the disk has largely settled down.

4. X-ray Eclipse Mapping

The Swift satellite has a huge amount of data in the X-ray, with coverage throughout the entire eruption often at the every-orbit level.
The SSS flux remains roughly constant (with a bit of a rise) from Days 14-33 (the duration of the optical light curve plateau), as predicted.
This provides an excellent stability for eclipse mapping of the SSS.
For Days 15-21, I see peristent but 'fuzzy' evidence in the folded light curve for primary eclipses with total duration of ~0.3 in phase and 25% in depth. The duration points to a fairly large source, while the depth points to plenty of flux coming from above the orbital plane. A reasonable fit is obtained from a uniform spherical source that fills the space inside the companion's orbit. This is similar to the case of the optical eclipse mapping. I interpret the X-ray source as being largely X-rays from the central SSS being Thompson scattered off the wind.
For Days 21-28, the X-rays become much more jittery, with some apparent deep eclipses, and other orbits with apparent eclipses offset in time from the conjunction, and other orbits having no apparent eclipse for our once-per-orbit sampling. This is all very confusing. I can only

think that we are seeing a combination of effects as the optical depth through the wind varies, the raised rims of the proto-disk cause classic X-ray dips, and perhaps the hot spot contributes also with eclipses.
For Days 28-33, the X-ray eclipses are unambiguously visible, all with apparent depths of 25% and full durations of 0.2 in phase. The low amplitude, even for a time when the companion star completely covers up the WD and the inner part of the accretion disk, points to an extended source of X-rays, or at least to a small source (the SSS) where a large fraction of the X-rays are scattered from a much larger region.
After Day 34, the SSS is largely turning off fast, and I see no real pattern in the folded light curves. That is, Swift sees U Sco to vary substantially with no obvious eclipses.

C. ECLIPSE TIMES

1. Offsets During Eruption (and why they change)

We have 12 good eclipse times from during the eruption and one from afterwards. The orbital phase of these is evaluated with my ephemeris from quiescence as based on 45 eclipse times from 2001-2009. The O-C of these eclipses differ significantly from zero. The offsets from zero are roughly linearly changing in time. For Days 15-20 the offset is -0.013 days or so, with this negative value meaning that the observed eclipse times are *before* the times predicted by the quiescent ephemeris. By Day 60, the O-C has shifted to +0.011 days or so. After the end of the eruption, on Day 110, the O-C is 0.000, which is back to the quiescent level.
Note, the offsets of eclipse times during eruption are significant, so they cannot be combined with quiescent eclipse times. So prior claims of measuring period changes in U Sco (and CI Aql) are certainly wrong.
What is going on is that the center of light is shifting, and so the time of minimum light is shifting relative to the orbital phases based on the stars orbits.. During the early days of the eruption, the optical light is entirely from the SSS wind which is centered on the WD, so the time of eclipse minimum light is close to the time of the inferior conjunction of the companion star. During quiescence, the optical light comes from both the bright inner regions of the disk plus the offset region of the hot spot (where the accretion stream hits the disk), with the result that the center of light has shifted away from the WD towards the hot spot resulting in a systematic shift of the eclipse times.
During the eruption, the center of light starts out at the WD (because the SSS wind is radial and centered on the WD) and slowly shifts as the offset accretion stream and hot spot get brighter. The positive offsets for Days ~50-63 are caused by the offset light being brighter (or farther out) than is normal during quiescence. So we well understand what is going on with the shifts, even though nothing like this has ever been seen before.

2. Period Change Across the *1999* Eruption

I have observed 16 eclipse times from 1989-1998, 45 eclipse times from 2001-2009, and one eclipse time in 2010 after the eruption is over. I also have observed one eclipse time from the 1945 eruption (from the eruption I discovered in the Harvard plates), three eclipse times from the 1999 eruption (from the literature), and 12 eclipse times from the 2010 eruption (observed by many of us). This is 78 eclipse times in all.

I fit the 45 eclipses from 2001-2009 to a simple linear ephemeris to get HJD(minimum)=2451234.5387 + N*1.23054695. This should be used as the fiducial definition of phase. The RMS scatter of the individual observed times about this (or any other) best fit is 3.9 minutes, which is greatly larger than most of the measurement errors in timing. The cause of this is ordinary flickering during the ingress and egress that 'tilt' the light curve and slightly bias the minima times. So the way to get better periods is to measure many eclipses so as to beat down the random intrinsic timing jitter. From the 2001-2009 interval, I can also fit for a parabolic term in the O-C diagram (i.e., a steady Pdot term, such as expected from conservative mass transfer). I find that Pdot must be rather small, with the best fit value negative, and it being consistent with zero to within two sigma. A negative Pdot works in the opposite direction of conservative mass transfer, which implies that the quiescent U Sco must have some angular momentum loss mechanism (e.g., due to magnetic fields and winds).

I have only recently realized that a substantial problem is that the steady period change (Pdot) is degenerate with the sudden period change across eruptions (DeltaP). That is, for the one-sigma smallest negative Pdot, the best fit O-C curve from 1987-2009 has a negative DeltaP, whereas for the one-sigma largest negative Pdot, the best fit has a positive DeltaP. (I find the same result for the 84 eclipse times that I have from 1926 to 2009 for the recurrent nova CI Aql, with the derived DeltaP across its 2000 eruption similarly has a best fit DeltaP being negative, even though DeltaP=0 is within the one-sigma range.) This degeneracy has substantially increased the error bars for my measures of DeltaP. The prospect of a negative DeltaP is daunting, because the nova mass ejection contributes a positive DeltaP, while dynamical 'friction' in the common envelope phase is certainly too small to work. So Martin et al. (2010, arXiv:1003.4207) have proposed a mechanism involving the magnetic field of the companion star operating on the ejected mass to carry away angular momentum.

Neverthless, for U Sco, I derive DeltaP = (+43 +- 69)x10^-7 days, and hence Mejecta=(43+-67)x10^-7 Msun. (For CI Aql, I derive Mejecta<1x10^-6 Msun.) This result will improve substantially soon as the post-eruption constraints on Pdot are improved greatly in the next few months. And in a few years, I will have a measure of the DeltaP across the 2010 eruption.

D. LINE PROFILES

1. 'Batman' Profiles

For Days 0-5, the line profiles (eg. of the Halpha, Hbeta, PaschenGamma, BracketGamma....) appear triple peaked, with the two outer peaks being sharp topped at around +-5000 km/s, and the center peak being rounded and broad. With appropriate scaling, these look like the profile of Batman viewed face-on, where the two outer peaks are the ears of Batman and the central peak is the top of Batman's cowl. These were new to me, and so I had previously highlighted them as a mystery.

I have now reviewed all the spectra of U Sco and determine what is going on systematically. I find that all the lines (optical and IR, hydrogen and non-hydrogen) have the same profiles at any given time. The Batman profiles are seen prominently up until Day 5 or so. After that, the 'ears' go away, and we see only single sharply peaked lines with very broad wings. But then, on Days 16-23, the hydrogen lines all become triple peaked, with the peaks at +- 1800 km/s and all three peaks are well isolated. So with two episodes of triple-peaking, perhaps we have two mechanisms.

Jen Andrews and Chris Gerardy have pointed out precedents for 'Batman profiles'. It turns out that such profiles are seen in Type IIn supernova and in other novae. Dave Lynch has been calling the profiles 'castellated' for novae. For the Type IIn SN1998S, Gerardy et al. (2000, AJ, 119, 2968) found Batmans and concluded that the 'ears' are caused by an expanding torus, with the Earth being near the equatorial plane. Fred Walter has found Batmans for YY Dor, Nove LMC 2009, V2672 Oph, and KT Eri. (A perhaps important note is that these are all recurrent novae or strong RN candidates.) Vanlandingham et al. (1996, MNRAS, 282, 563) has found Batmans for V838 Her (another strong RN candidate), Lynch et al. (2006, ApJ, 638, 987) for V1187 Sco, and Kamath et al. (2005, MNRAS, 361, 1165) for V1494 Aql. All of these papers attribute the Batman profiles to an expanding torus with the Earth being in the equatorial plane. (Indeed, many of the Batman novae are eclipsing systems.) U Sco is seen nearly edge on, so we have maybe should have *expected* the Batman profiles. The expanding torus would be caused by the accretion disk being entrained in the expanding shell, resulting in density enhancements over a toroidal region with high velocity. So, with U Sco's known high inclination and the many precedents, we now know the cause of the Batman profiles.

To see the two ears of the Batman profile, we have to see the backside of the torus, and this implies that at least part of the shell is optically thin. I think that this is an important point. During the first 5 days of the eruption, we can see to the backside of the shell! How can this be? Taking a cue from Jeremy Drake, the shell will look bipolar due to the accretion disk (like a pair of opposing mushroom clouds), with a low density region in the equatorial plane. Given the known inclination of U Sco (~82 degrees), our line of sight to the back of the torus will pass just below the edge of the 'upper' mushroom cloud, and so we'll have a relatively clear line-of-sight.

2. 10,000 km/s

The expansion velocity of the U Sco is variously given as HWZI=5500 km/s (Arai et al. CBET 2152), HWHM=3800 km/s (Anupama et al. ATel 2411), and HWZI=5000 km/s (Ashok et al. CBET 2153), while later reports quote 3000-4000 km/s (Ness, ATel 2469). [This is expected as the 1999 eruption had the line widths decreasing linearly with time.]
However, D. P. K. Banerjee, in a private communication, has pointed out that the line profiles have consistent wings in early times that extend out to expansion velocities of 10,000 km/s. These wings are outside the 'Batman' profiles, are seen for Br-gamma, H-alpha, and N-I lines, and were visible in spectra from the 1999 eruption. Banerjee's discovery is quite astounding, as here we see a nova ejecting material at supernova velocities. Banerjee's discovery presents a strong challenge to theorists.

E. UNIVERSAL DECLINE LAW

1. Testing Prediction with Stromgren 'y'

Hachisu & Kato (2006, ApJSupp, 167, 59; and many followup papers) have presented a Universal Decline Law ('UDL') for nova light curves. In general, starting soon after the peak, the nova continuum flux will fall of as the -1.75 power of time (4.4 mag per log-time) and after a break time will have the flux decline as the -3.5 power of time (7.5 mag per log-time). The time of the break will depend primarily on the mass and composiiton of the WD. A complication is that the usual V-band magnitudes also include line flux, so there could be offsets from the UDL that predicts the *continuum* flux. They present the solution of looking at the light curve in the Stromgren 'y' band as this avoids most of the emission line flux.
For the purpose of testing the UDL prediction, Gerald Handler (at SAAO), Hiroyuki Maehara (at Kwasan Observatory), Seiichiro Kiyota (VSOLJ, Tsukuba Japan) James Clem (at CTIO), Arlo Landolt (at Lowell) all made series of magnitudes in Stromgren 'y'. The result is a near perfect fulfillment of the predictions of the UDL. The fitted slope is 4.4 mag per log-time up until a break around Day 24 followed by a 7.6 mag per log-time decline after the break. Nice.
Despite a startlingly succesful prediction, I have three worries/questions: First, if the quiescent light is subtracted out of the flux in the light curve, the late time decline is more like 10.1 mag per log-time. The derivation of the UDL makes no reference to the quiescent flux, so I think that this should be subtracted out, resulting in a non-perfect agreement. Second, the derivation of the UDL is based on the presumption that the light is dominated by the expanding shell, whereas

the light from U Sco after Day 15 is dominated by the SSS wind and after Day 41 by the accretion disk, so it seems that the UDL is irrelevant after the first 15 days. Third, the initial decline has various inflections (eg., due to the plateau), so an alternative fit is one with a break at 6 days, with the slopes (3.7 and 8.0 mag per log-time) being good for the UDL, with this fit ignoring all the data after the start plateau (with the pleateau light not being relevant for the UDL). These points need clarifiation, in particular as to whether the plateau light should be included in the fit.

2. Break Time and the Composition of the WD

The time of the break in the UDL depends on the WD mass and composition. Table 10 of the Hachisu & Kato paper give a list of the break times for WD masses from 0.6-1.30 Msun and for CO and Neon WDs. The U Sco WD is more like 1.37 Msun, so an extrapolation or further analysis are needed. With an extrapolation, the CO WDs might have a break at perhaps 10 days, while the Neon WDs might have a break at 15-20 days. This is to be compared to the fits which give break times of 24 days or 6 days depending on whether the plateau light is included or not. It seems that with a little theoretical guidance (break times for 1.37 Msun, whether to use the plateau), we can get a good answer to whether the U Sco WD is CO or Neon in composition.

F. LOOKING FORWARD

1. Mejecta From Spectral Energy Distribution

Shara et al. (2010, ApJLett, 712, L143) put forth a new idea that the total mass ejected is simply proportional to the total radiated energy. The constant of proportionality is established to be a constant and evaluated by their many nova models. So now we have a new way to measure Mejecta. And this way is independent from all other ways.
To get this new method working, we have to have full spectral energy distributions over a wide spectral range over the entire time of the eruption. And we also need a reliable distance so as to convert the observed flux into luminosity. Before this U Sco eruption, no nova comes close to being well enough observed, with few having even one day of UV or X-ray observations, much less far into the IR. (The 2006 eruption of RS Oph comes close, but this is still missing the IR and the full time coverage.) And almost all nova have factor-of-2 distance uncertainties, which result in 4X errors in luminosity and 4X errors in Mejecta. (The MMRD relations have a factor of two uncertainty, and other methods are only worse in accuracy. Only novae in globulars [T Sco] and in other galaxies have accurate distances, except...)
U Sco is the perfect nova to which to apply the new Shara method.
Only U Sco has daily X-ray plus UV plus UBVRIJHK plus midIR throughout the entire eruption. Only U Sco has an accurate distance (12+-2 kpc) because

only U Sco has *total* eclipses which allow for a reliable blackbody distance (based on the light from the un-irradiated hemisphere of the companion star alone). To this end, Ashley Pagnotta and Eric Schlegel are working on the Swift data to get the X-ray and UV contributions to the daily spectral energy distribution. Soon, this will be put together with the UBVRIJHK and the WISE midIR data to get the total radiated energy and then the Mejecta for U Sco.

2. Abundances, Temperature, ... From Global Spectral Analysis

Our community has an enormous amount of spectroscopy data, from the X-ray (daily by Swift and with high spectral resolution by Chandra, Suzaku, and XMM), the UV (daily with the Swift UVOT), the optical (daily by Fred Walter and many other people), and the IR (by Howie Marion, D.P.K. Banerjee, Mark Rushton, David Lynch, and others). Most of these observers are working on papers describing their own data sets, with varied analyses.

However, our community has a wonderful opportunity to put all of this data together for a global analysis. Instead of having conflicting values derived for spectra in differing wavelengths over different time intervals, a global analysis can reconcile all the disperate input into a consensus value. For example, a conclusion that the carbon abundance is low would be weak if based on the X-ray spectra alone, yet would be strong when confirmed with the UV, optical, and IR spectra. Likely, the global analysis will result in a complex picture, with this being good. (To recall the old story, it is better to get a picture of the whole elephant than to be confused with descriptions of the elephant's trunk, tail, and legs.)

To this end, I have recruited Greg Schwarz and Bob Williams to perform this global analysis. They are the best and most knowledgeable for nova spectral analysis. I have gotten them most of the spectra, although Ashley Pagnotta and Eric Schlegel are still producing the Swift X-ray and UV spectra. Schwarz & Williams are delaying a bit to allow individual observers to well publish their own data. (The individual analyses are valuable as they will cover many points that the global analysis can't cover.) Their analysis will take a while, and I don't know how much help they would appreciate.

The most important questions for the global analysis are the abundances, the velocity structure, and the masses. Is the accreted matter really hydrogen deficient? Does the ejecta have any material pointing to dredge-up? If so, what does this imply about the composition of the WD? Can the many huge assumptions in the Mejecta calculation based on line fluxes be tested/confirmed/measured so as to get a measure of Mejecta that is better than the current ~3-orders-of-magnitude accuracy? How do the physical conditions in the 'Batman ears' differ from the rest of the shell? What is the density as a function of velocity for the initial shell ejection and what is the velocity, temperature, and ejection

rate as a function of time for the SSS wind?
So sometime in a few months, their global analysis should give unique and reliable results for many of the key questions on the physics of the nova ejecta.

Cheers,
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