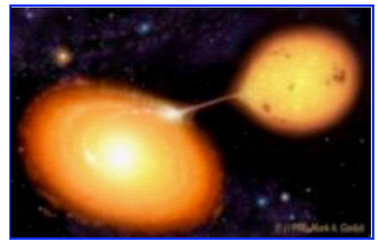
Variable Star of the Season, July 2009

The recurrent nova U Scorpii

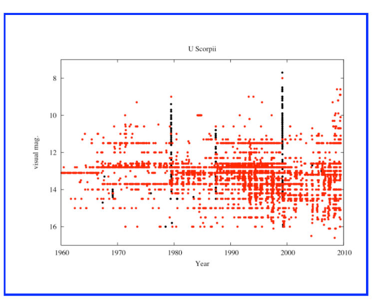
The middle of the year brings the Galactic center into clearest night time view, including the rich star fields of Sagittarius and Ophiuchus, and one of the most striking constellations in the sky -- Scorpius, the giant scorpion of Greek mythology that brought mighty Orion down to size. Scorpius cuts a dramatic figure across the plane of the Milky Way. Although Sagittarius and Ophiuchus both have many more known variables, the Scorpion has its fair share, including a number of Galactic novae. One of the most famous (and most exciting) of the novae of the modern era lies in Scorpius as well -- the recurrent nova U Scorpii. This (very very!) fast nova was first spotted in 1863 by Pogson, and has recurred many times since then. This season, it is the target for a major AAVSO observing campaign, and thus makes a fitting Variable Star of the Season for June 2009.



An artist's impression of a cataclysmic variable. The gravitational pull of the white dwarf (left) pulls matter from the secondary star (right), which forms an accretion disk around the white dwarf. Matter orbiting in this accretion disk eventually loses enough angular momentum that it spirals onto the white dwarf. (Image credit: Mark A. Garlick)

U Scorpii: a (very) fast history

U Sco was first discovered during its 1863 outburst by the English astronomer N.R. Pogson, then director of the Madras Observatory in India. Pogson tracked the nova during its very brief period of visibility, finding it at magnitude 9.1 on May 20th of that year. Within a week, it faded to magnitude 12.8, and by June 10, it was gone. It wasn't seen again for more than 80 years, when it was detected by Helen Thomas in her survey of archival Harvard patrol plates. U Sco was found to have been in outburst on May 12, 1906, and again on June 21, 1936. Thomas also noted that both the rise and decline times of U Sco were very short; during the 1936 outburst, the star faded by more than a magnitude in less than nine hours, and had faded by six and a half magnitudes in one month. The rediscovery of U Scorpii and the measurement of its light curve made it clear that it was not only a member of the exclusive club of *recurrent novae*, but that it was one of the fastest novae. Indeed, it now holds the record as **the fastest** known nova.



U Sco has the largest number of recorded outbursts of all the recurrent novae, with outbursts detected in 1863, 1906, 1917, 1936, 1945, 1969, 1979, 1987, and 1999. The times between outbursts seem to be fairly regular -- around 10 years or an integer multiple of that (suggesting a missed outburst in between). But despite the large number of outbursts, U Sco remains one of the least understood recurrent novae. The extremely fast rise and fast decay mean observers have little or no warning when this star undergoes outburst, and so there is precious little time to study the properties of the system in

The AAVSO visual light curve of U Sco. Black points are positive observations; red points are fainter-than observations. U Sco is very faint in quiescence, typically at or below m(vis)=18.0.

outburst. Webbink et al (1987) noted that it wasn't until the 1979 outburst that we had good measures of the spectroscopic properties of U Sco, and lots of questions remain about this system (more on that later).

Novae: dwarf, classical, or recurrent?

The *cataclysmic variables* are a diverse group of binary variable stars composed of a white dwarf primary and a main-sequence or giant secondary star. The stars orbit closely enough about one another that mass is transferred from the secondary star to the white dwarf. Since that process of mass transfer can generate lots of energy, it is what makes them vary. And that variability can be "cataclysmic" in that these stars can (sometimes) get considerably brighter in a very short period of time.

What makes the class so diverse is how quickly mass transfer progresses, and what happens to the matter when it gets to the white dwarf. The word "nova" is used for many of these stars because one of their behaviors is to suddenly brighten, sometimes from telescopic invisibility to obvious naked-eye brightness. When this happens, they can briefly appear as a "new star" (or "nova stella") in the sky, hence the name. But "nova" is used for a very broad range of behavior. Three commonly-discussed types are *dwarf novae*, *classical novae*, and *recurrent novae*.

These classes differ in two ways: the reason for their sudden light increase, and the amount by which they brighten. The much more common *dwarf novae* brighten because the matter flow being accreted from the secondary to the white dwarf can, at somewhat random intervals, get hotter. When it gets hotter, it gets much, much brighter. A dwarf nova outburst can increase the luminosity of these binary systems by a factor of 100 or more for several days or weeks until the accretion disk around the white dwarf can cool down again. This repeats again and again, taking anywhere from a few days to a few years, depending on the star.

The *classical novae* are quite a bit more spectacular. When they go into outburst, they can brighten by a factor of *ten thousand* or more! They still accrete matter like dwarf novae do, but in the classical novae, the matter that piles up on the white dwarf's surface gets hotter and denser over time and eventually undergoes a thermonuclear reaction. These stars are like giant thermonuclear bombs, temporarily flaring up with the brightness of ten thousand Suns. The light curves of individual novae vary, but typically they brighten from telescopic invisibility over the course of many hours to a day or two, reach a peak, and then fade away to telescopic invisibility over times ranging from days to several months, *perhaps* never to be seen as novae again, at least not in our lifetimes.

Then there's the third class, the *recurrent novae*, to which our Variable Star of the Season U Scorpii belongs. What are those?

Recurrent novae: an exclusive club

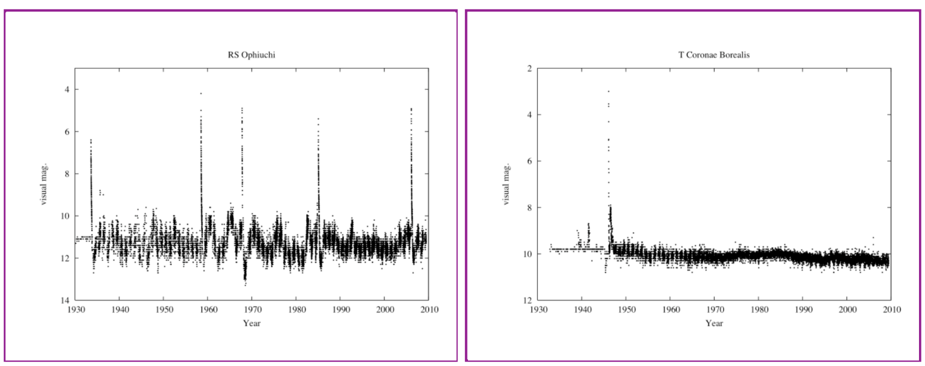
The recurrent novae are like classical novae in that they consist of a white dwarf primary star accreting mass from a stellar secondary. Accreted material builds up on the white dwarf and eventually reaches the temperature and pressure required for thermonuclear ignition. When it does, the shell of accreted material undergoes thermonuclear fusion, rapidly increasing the brightness of the system and ejecting this shell of material off the surface of the white dwarf. Where recurrent novae differ from the classical novae is that they **repeat** on observable timescales. Classical novae are not thought to repeat for hundreds or thousands of years (at the very least), but recurrent novae can recur on timescales of years or decades.

It is possible that there are not two classes of novae, but rather a continuum of recurrence times. However, the recurrent novae as a group also have higher mass accretion rates than classical novae on average; spectroscopic evidence seems to suggest that the secondaries in recurrent novae are all giant stars. The weaker surface gravities of a giant secondary star would make it easier for the white dwarf primaries to pull material off. The short recurrence time also suggests that the white dwarf primary must be closer to the Chandrasekhar limit for recurrent novae, simply because their stronger surface gravities are better able to compress the accreted hydrogen to thermonuclear fusion pressure and temperature sooner following a nova outburst.

What is most interesting about the recurrent novae is their relative scarcity. While there might be a dozen or more new novae each year, there are only ten confirmed recurrent novae known in the Milky Way at the present time: T Pyx, IM Nor, CI Aql, V2487 Oph, U Sco, V394 CrA, T CrB, RS Oph, V745 Sco, and V3890 Sgr. This list is almost certainly incomplete, and it is likely some known "classical novae" are really recurrent novae whose recurrent outbursts were missed, or have not had time to recur yet. Indeed, this list has increased by one during the past year with the addition of V2487 Oph, due to the diligent work of Brad Schaefer and his students, who recently combed through the plate archives of the Harvard and Sonneberg Observatories in search of missed novae. They found V2487 Oph (Nova Ophiuchus 1998) exhibited an earlier outburst in the year 1900.

Louisiana State University student Ashley Pagnotta examining an archival plate at the Sonneberg Observatory, Thuringen, Germany in 2008. Pagnotta et al discovered an earlier outburst of V2487 Oph (Nova Oph 1998) that occurred in the year 1900, making it the tenth known galactic recurrent nova. (Image credit: Ashley Pagnotta LSU)

But even with the one additional member, the difference in numbers between the two classes is striking. Why are they rarer than typical novae? For one, most white dwarfs, even in accreting binary systems, aren't anywhere near the Chandrasekhar limit of 1.4 solar masses -- they're usually around 0.6 solar masses or so. And it isn't likely that they start out as low-mass white dwarfs and grow over time. When nova eruptions occur, the white dwarf actually sheds a lot of mass, and it's possible that white dwarfs in nova systems never grow very much regardless of how much of their companion's mass they accrete. Either something peculiar happens in recurrent nova systems to allow the white dwarf to grow, or they started out massive to begin with. If the latter, the white dwarf probably originated from a more massive star, perhaps several solar masses. Massive stars are rarer than lower mass stars -- the clouds that form stars preferentially create lower-mass stars. So perhaps recurrent novae only originate from binary systems in which one or both stars starts off having several solar masses.



Long-term light curves of RS Oph (left) and T CrB (right).

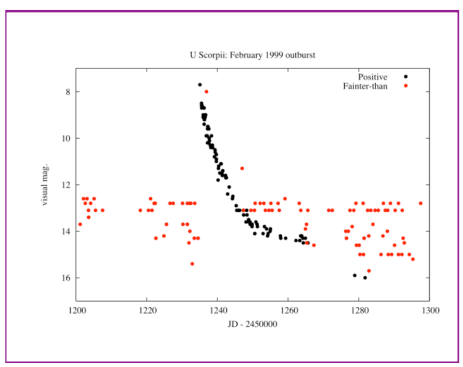
The recurrent novae aren't all alike either, which suggests there are still more peculiarities going on. The most obvious division is by orbital period. Some, like T Pyx and U Sco, have relatively short orbital periods (T Pyx has the shortest at a mere 1.8 hours; U Sco's is a little over 1.2 days). Others, like RS Oph and T CrB have periods of *hundreds* of days, far longer than most cataclysmic variables, and more akin to the **symbiotic stars** like Z Andromedae (whose orbital period is about 725 days). The recurrent novae all have somewhat different light curves as well. For example, the long-term light curve of RS Oph shows a lot of variability during quiescence, including years-long active periods where it brightens by a magnitude or more. The long-term light curve of T CrB is a lot more sedate. It doesn't show the same active periods as RS Oph, and while the quiescent light level certainly changes, they're not as large as those of RS Oph.

Although they have very different orbital periods and somewhat different light curves, the outburst mechanism for both groups of recurrent novae are probably the same, namely a thermonuclear runaway in built-up material on the white dwarf surface itself. Just as in classical novae, recurrent novae go into outburst whenever enough mass builds up to push the star over a critical temperature and density sufficient to cause thermonuclear burning. This burning reaction continues until either all the nuclear fuel on the surface is consumed, or enough of the accreted matter is blasted off of the star to stop the reaction.

This scenario wasn't always as clear, and there are still occasional suggestions (e.g. King & Pringle 2009) that some recurrent novae could in fact be dwarf-nova like outbursts, but on a larger scale. The infrequently-erupting dwarf novae known as *WZ Sagittae stars* used to be lumped in with the recurrent novae, though they're now known to be otherwise ordinary dwarf novae with very low mass accretion rates and very short orbital periods. And there are also some confusing observational results on one recurrent nova that (maybe) clouds the picture. Rupen, Mioduszewski, and Sokoloski 2009 found evidence for radio jets occurring shortly after the most recent RS Oph outburst. According to models of relativistic jets, jet formation is tied to the existence of an accretion disk. However, any accretion disk around a nova would be destroyed in a thermonuclear outburst on the white dwarf, and so the presence of jets is confusing. Despite these points, the general concensus is that the thermonuclear outburst model explains the behavior of these systems more completely and effectively than the thermal instability model. More work is obviously needed to fully understand this and all other recurrent novae, and as always, more observations (including yours) are needed.

U Scorpii -- coming soon to a sky near you?

In 2005, Brad Schaefer proposed that in nova systems which undergo thermonuclear runaways, the recurrence time should be relatively constant. The mass accretion required to initiate a nova event in a given system is essentially constant, and the accretion rate should not vary much (at least in the short-period systems). Further, he proposed that since the recurrence time of U Sco is fairly regular (about ten years), U Sco should undergo a nova event some time around 2009 (2009.3 +/- 1 year, to be precise). That's **right now**! In 2007, Brad approached the AAVSO with a project to provide close monitoring of this system during the proposed outburst window, to see if we can catch this very (very very!) fast nova in the act. If we do, telescopes all around the world and in space will be turned toward this star to provide what may be the best-observed and best-studied outburst of U Sco in its history.



The February 1999 outburst of U Scorpii. Note how quickly the nova declines from its maximum (m = 7.7). It faded below the reach of most observers within 30 days. U Sco is the fastest of the "fast novae".

Since mid-2008, observers around the world have been observing U Sco and reporting their observations, and Schaefer and his students and collaborators have been paying close attention to see whether we can catch this speedy nova right at the start of its rise. Observers like you have been key to this project, providing critically important information, including confirmation in early 2009 that U Sco did not erupt and fade during its late-2008 solar conjunction. And it will almost certainly be an observer like you who sounds the alert that U Sco is on the rise once again, whenever it goes into outburst.

The AAVSO is currently running an observing campaign on U Sco and observers are encouraged to observe this star as often as you can. All observations -- visual and instrumental -- are important, and "fainter-than" observations are just as critical as positive observations, particularly if you can detect comparison stars near the faint end of the sequence. In his own words, Brad Schaefer explains the current state of the project and what **you** can do to help with this exciting campaign:

> "How can **you** help? One important way is to check U Sco every night to see if it has started up. The rise from quiescence (V~18.5) to peak (V=7.5) takes about **four hours**, and the decline from peak is by three magnitudes in the first 2.6 days. U Sco is the all-time fastest nova. And this means that we need the all-time fastest discovery and reaction to be able to get the big telescopes onto U Sco during its peak. AAVSO Headquarters is serving as a 24-7 clearinghouse for your discovery observations. Even if you don't discover U Sco going up, you can follow it going down with many magnitude estimates. AAVSO light curves are always better than the professionals because their coverage is so much better. If you have CCD cameras, you might try following U Sco deep (use standard BVRI filters if you can), and you might try taking long fast time series photometry so as to catch the eclipses turning back on, or to catch the flickering turning back on."
>
> "I have formed a large international collaboration to closely measure U Sco in eruption with high time resolution, spectroscopy, and photometry across all part of the electromagnetic spectrum. Here is a summary of the groups and telescopes that have already signed up:"
>
> - X-Ray: Swift, Suzaku, Chandra, XMM-Newton
> - Ultraviolet: Swift
> - Optical: CTIO, PROMPT, SALT, Liverpool 2.0-meter, Faulkes-North, Center for Backyard Astrophysics, AAVSO
> - Infrared: CTIO, IRTF, Lick Observatory
> - Radio: NRAO
>
> "Undoubtedly, many more observers will look with every way imaginable. But what we all need is *fast* notice that it is up. We only have a day at peak, and late notice would spoil it. So check U Sco even near the Full Moon and in twilight."
>
> "The bragging rights for discovering a U Sco eruption are large. But most important is the fun at seeing this unique prototype going up so as to give the fastest notice so as to enable the best deep science."

So the goals for the U Sco campaign are really two-fold. First, is the detection of the nova eruption itself. Will it occur during this predicted one-year window? If so (or if not) what does that tell us about the thermonuclear trigger theory of recurrent novae? Second is the wealth of information which could come from detecting U Scorpii right at its maximum. As Webbink et al pointed out, we have learned a number of things about U Scorpii during the past few eruptions. We know that the system has a very high ejection velocity (probably more than 7500 kilometers per second, not much below what we see in supernovae). Precise measurements of the spectral properties of U Sco at maximum can tell us about the composition of the accreted material, its ejection velocity, how much material gets ejected, and how long the thermonuclear runaway continues.

All of those questions also point to another, much larger underlying question, namely this: **are recurrent novae the progenitors for Type-Ia supernovae?** As I mentioned earlier, most accreting white dwarfs -- even those in classical novae systems -- aren't very massive, and don't gain much mass during their accreting lives. Thus most classical novae are unlikely to ever reach the Chandrasekhar mass limit and collapse into neutron stars, which is the cause of

Type-Ia supernovae. Is it possible that recurrent novae, with their massive white dwarf primaries just under the Chandrasekhar limit, are supernovae in waiting? There is evidence that both RS Ophiuchi and U Sco are good candidates for future supernovae, though only time will tell. Could all recurrent novae generate Type-Ia supernovae or only some of them? Could U Sco be one of them? If so, when? Maybe the answers will lie in the next outburst of U Scorpii.

Is *four hours* enough time to observe, get the word out, and turn the telescopic eyes of the world toward this enigmatic system? That's what we're hoping to find out! And that's why we hope all observers, wherever you are and however you observe will turn your eyes toward Scorpius this season. Perhaps -- if you're really lucky -- you'll catch a glimpse of history in the making. It just might be your observations that help solve the mystery of our July 2009 Variable Star of the Season, U Sco.

Further reading

- Customizable charts for U Sco
- The AAVSO Observing Campaign: Long-Term Monitoring of the Recurrent Nova U Scorpii (see also Alert Notice 367)
- Schaefer, B.E., 2009, "U Scorpii: Recurrent Nova About to Blow Up?", *Sky & Telescope Magazine's* "Observing Blog", April 29, 2009
- Variable Stars of the Season: RS Oph by Kerriann Malatesta and T Pyx by Kate Davis
- Hachisu, I. et al., 2000, A Theoretical Light-Curve Model for the 1999 Outburst of U Scorpii, *Astrophysical Journal* 528, L97
- Schaefer, B.E., 2005, A Test of Nova Trigger Theory, *Astrophysical Journal* 621, L53
- Sekiguchi, K., 1995, Recurrent Novae, *Astrophysics & Space Sci.* 230, 75
- Simonsen, M., 2009, Recurrent Novae, *AAVSO Cataclysmic Variable Section*
- Webbink, R.F., 1976, The Outbursts of the Recurrent Nova T Coronae Borealis, *JAAVSO* 5, 26
- Webbink, R.F. et al., 1987, The Nature Of The Recurrent Novae, *Astrophysical Journal* 314, 653

This Variable Star of the Season was prepared by Dr. Matthew Templeton, AAVSO. Thanks to Dr. Arne Henden (AAVSO) and Ashley Pagnotta (LSU) for assistance.

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