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The spectral evolution of recurrent nova U Sco in the 2010 outburst

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Abstract. Spectrophotometric synoptic observations of the recurrent Nova U Sco 2010 are presented. The evolution of the optical spectrum is discussed and analyzed. A short lived nebular phase was observed for the first time in this nova. A 3D photoionization simulation for the unresolved nova shell was calculated. Model results indicate an overabundance of Neon and the presence of gas condensations in the shell. An ejected mass in excess of $3 \times 10^{-6} M_{\odot}$ is suggested.

Key words. Stars: novae, cataclysmic variables – Stars: individual U Sco – Stars: white dwarfs – Accretion, accretion disks – Stars – supernovae

1. Introduction

Recurrent novae (RN) are located in the upper right corner of the unstable region in the $\dot{M}{\times}M_1$ diagram, with typical recurrence times of 10 up to 100 years. Their recurrence times seems to depend essentially on the white dwarf mass and mass accretion rate, being almost insensible to the core temperature (Townsley 2008). U Sco belongs to a subclass of fast and short recurrence time RN together with V394 CrA and LMC-RN. Those objects are known as the single degenerate binary path to type Ia supernovae (SN) due to the possibly high white dwarf mass and high mass accretion rate. The trivial condition for evolution towards a SN Ia is that the mass accumulated between outbursts is larger than the mass ejected during the outbursts over secular time-scales. Outburst conditions and mass ejection efficiency change rapidly as the white dwarf approaches the Chandrasekhar limit. For instance, the ignition mass and time between outbursts depend strongly on the white dwarf mass. The long term evolution for accretion rates around $10^{-7} M_{\odot}$/yr has not been modeled yet (Idan et al., these proceedings). On the other hand, ejected mass estimates from spectroscopic diagnostic of the shell can be pursued more effectively during the nebular phase. However, there are large uncertainties in the photoionization models and biases related to the presence of neglected neutral gas clumps in the ejecta. U Sco has been considered the SN Ia progenitor prototype among cataclysmic variables with a primary mass $M_1 = 1.55{\pm}0.24$

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$M_\odot$ (Thoroughgood et al. 2001) and an average recurrence time of 10.2 years.

2. Observations and spectral evolution

The observations were taken with the Goodman spectrograph at SOAR 4.1 m telescope as part of a synoptic survey of novae in outburst. A total of 26 intermediate resolution (R~2800) spectra covering from 345 to 900 nm were obtained from less than a day to 7 months after visual maximum (Diaz et al. 2010). These are Target of Opportunity service observations with pointing executed in queue mode. Soon after maximum spectrum shows wide and saturated lines changing on time-scales of a few hours. Between day 2 and 9 a narrow component appear over the broad recombination lines in P_N class spectrum (Fig 1). Radial velocity measurements of those components show high values consistent with the K_2 semi-amplitude measured by (Thoroughgood et al. 2001). We interpret this narrow emission component as coming from the secondary star illuminated by the receding nova photosphere. By day 23 all low ionization metal lines have disappeared while the identification of lines from highly ionized species like NV and OVI is plausible.

In contrast with previous observations of U Sco in outburst the spectrum in 2010 developed a nebular component, clearly seen by day 51. Strong and broad [OIII], [NII] and [NeIII] lines presenting FWZI comparable to the recombination lines at day are seen (Fig. 2). The nebular phase was short lived with lines fading considerably after 2 months. This may eventually explain the missing nebular phase in previous outbursts. In addition, it happened a the very end of the supersoft phase (Schaefer et al. 2010). A significant fraction of low density gas in the shell and enough ionizing flux are required in order to produce a conspicuous nebular spectrum.

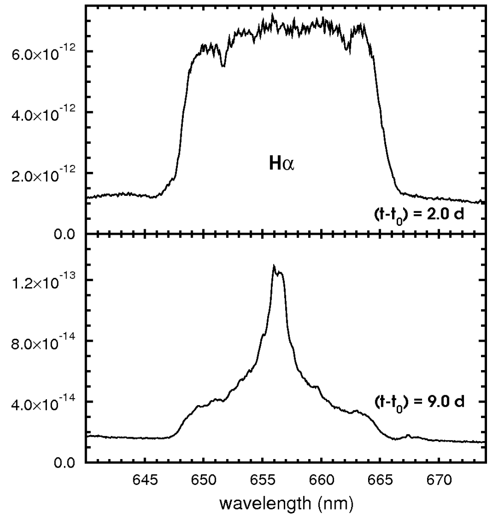

Fig. 1. Development of a narrow component in the recombination lines of U Sco. Ordinate unit is calibrated flux in $erg.cm^{-2}.s^{-1}.\AA^{-1}$.

3. X-ray observations and photoionization models

X-ray observations by SWIFT/XRT taken almost simultaneously to ground based spectroscopy were used to constrain the ionizing SED in our shell photoionization models. A soft (kT_{BB} ~65 eV) component was measured by day 52. Equivalent model fittings including a thermal breemstrahlung (kT_{Br} ~350 eV) component and a blackbody (kT_{BB} ~72 eV) were calculated. The model line fluxes are not significantly affected by the addition of such a harder component. However, the extrapolation of the soft X-ray spectrum towards the EUV range (which is responsible for most of the photoionization heating) is difficult because the ionizing SED blancketing in the EUV depends strongly on the helium abundance which, on its turn, is highly uncertain in this object.

An extensive grid of models were computed aiming to constrain the physical conditions in the shell, in particular the ejected mass. Grids for day 51 and 75 were computed using the RAINY3D code (Moraes & Diaz 2011) which drives the photoionization code

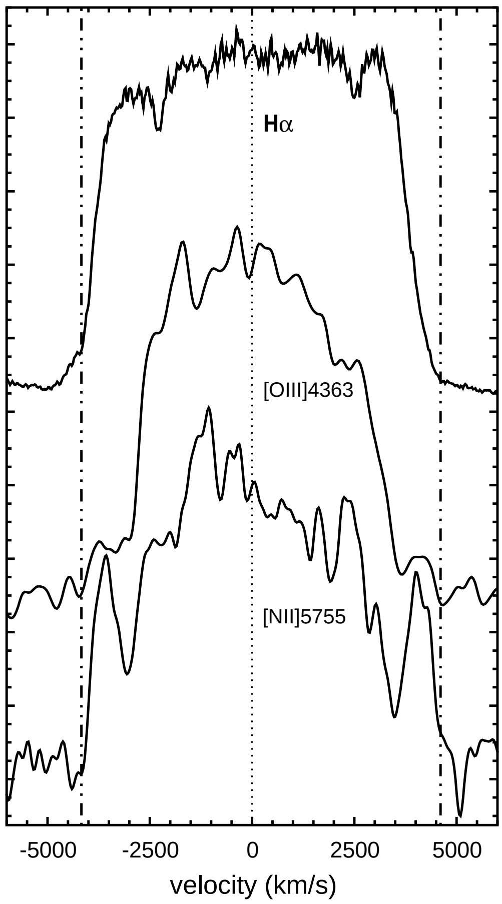

Fig. 2. Comparison between the FWZI of the nebular lines during nebular phase and Hα before the narrow line phase.

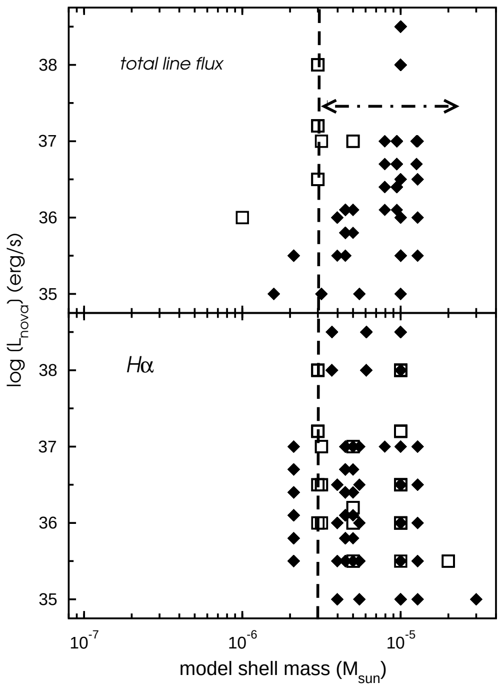

Fig. 3. Model results for days 51 and 75. All models in the grid having the correct total line flux (top) or Hα flux (bottom) are shown. The squares correspond to 3D clumpy models while the diamonds represent the results for shells with spherically symmetric mass distribution. The horizontal arrow indicate the approximate shell mass range of viable shell models.

CLOUDY (Ferland et al. 1998) as a subroutine. A total of 4334 spherically symmetric models and 127 clumpy 3D models were simulated. The model input parameters are: (i) The ionizing SED luminosity and temperature. (ii) The chemical abundances were taken from the literature. In particular, the helium abundance was found to be lower than those estimated in previous works with a lower limit of ~0.2 by number. Therefore, a wide range of [0.1-2] was allowed in the grid. (iii) The shell mass. (iv) The shell radius constrained by the measured expansion velocity of 4600 km/s. (v) Finally, the distance was free scaled by the total emission line flux between 4.0 and 13.5 kpc.

The unusual auroral to nebular ratios can be only explained by depopulation of upper nebular levels in a high density gas. This would set a constraint on the electron density $N_e \sim 10^7$ cm^{-3} in the [OIII] and [NII] line emission regions, indicating that condensations may play an important role in the mass distribution and cooling of the ejecta. It is well known that condensations may form soon after the nova outburst by Rayleigh-Taylor and thermal instabilities. Such gas clumps were incorporated in our models as gaussian density enhancements randomly distributed within a spherically symmetric background shell. The primary effect of the presence of clumps is the stratification in the gas ionization and the projection of shadows in the outer shell. A wide range of line ratios and fluxes can be obtained depending on the shell mass fraction (f_c) contained in clumps.

Due to the small number of lines the model solutions are highly degenerate in the parameter space. However, by using grids these models are reliable for constraining the boundaries of viable parameter values. A total of 4334 spherically symmetric models and 127 clumpy 3D models were computed. We robustly selected potential solutions as those which reproduce the observed total emission line flux and those that reproduce the observed Hα flux (Fig. 3). It is interesting to note that none of the spherically symmetric models could reproduce the observed auroral-to-nebular ratios. Both clumpy and spherically symmetric models require Neon overabundances of at least 10 times the solar values. No viable solution for luminosities below 10^{36} erg/s and ejecta masses below $3 \times 10^{-6} M_{\odot}$ could be found. Such a mass loss in the last outburst can be compared with the current mass accretion rate of $2.5 \times 10^{-7} M_{\odot}$/yr (Matsumoto et al. 2003). By assuming the historical average for the recurrence time and also considering that the 2010 outburst was typical in terms of mass loss one finds that the white dwarf in U Sco is not gaining mass.

4. Conclusions

A narrow line system was observed in U Sco a few days after maximum, possibly produced in the irradiation of the secondary star by the contracting nova photosphere. An elusive nebular phase can be formed in U Sco type recurrent novae, allowing a much more detailed diagnostic of the shell and central source. This brief phase extended into the X-ray supersoft source decline. The shell emission during the nebular phase shows evidence of highly structured mass distribution. Neon forbidden lines have been observed and the photoionization models indicate that $[Ne/H] \gtrsim 1.0$. Finally, if future outbursts are similar to the one seen in 2010, there may be no secular mass gain by the white dwarf in this RN.

5. Discussion

ELENA MASON: Did you compute [He/H] abundances for U Sco? and, if so, which is the value you get and how does it compare with past observations?

MARCOS DIAZ: We have only a lower limit around 0.2 by number, which is considerably lower than previous values.

IZUMI HACHIZU: Does the estimated mass of the shell depends on the assumed distance to U Sco?

MARCOS DIAZ: Yes. A wide range in distance from 4 to 13.5 kpc was used as a scaling parameter for the line fluxes. Most models in the grid scaled for distances below 8 kpc.

MARTIN HENZE: When you say you used the X-ray spectrum as an input for your observations, do you mean the SED itself or a parametrization?

MARCOS DIAZ: The ionizing spectrum was parametrized in luminosity and temperature. We used both blackbodies and Rauch NLTE high temperature stellar atmosphere models.

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