Mem. S.A.It. Vol. 93, 44

Memorie della

X-ray observations of accreting and burning white dwarfs.

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Received: 30 January 2022; Accepted: 29 May 2022

Abstract. This is a program of observation of white dwarfs (WDs) in binaries that accrete and burn hydrogen, often exploding as novae. We use the X-rays, including high spectral resolution and timing studies, to explore the evolution of these binaries and identify massive white dwarfs that may end as type Ia supernovae or in an accretion induced collapse. We study both quiescent sources during accretion, and supersoft X-ray sources where burning continues in a shell after the nova outburst, with extremely high effective temperature of several hundred thousand K, up to a million K.

Key words. (stars:) novae; cataclysmic variables; (stars:) individual: N SMC 2016; N LMC2009; V407 Lup; V2491 Cyg; KT Eri; EY Cyg; V794 Aql; X-rays: stars; Astrophysics - High Energy Astrophysical Phenomena; Astrophysics - Solar and Stellar Astrophysics

1. Introduction

The X-ray range is particularly interesting to study quiescent novae and all other cataclysmic variables (CVs). In disc accretors, by converting gravitational into electromagnetic energy, the mass accretion rate $\dot{m}$ powers the X-ray luminosity of the accretion disc boundary layer. Thus, it can be estimated with a model fit of plasma in collisional ionization equilibrium often with a gradient of plasma temperature (Mukai et al. 2003). Measuring and fitting the complete X-ray spectrum is fundamental for this aim. The hot plasma's maximum temperature is also directly related to the WD mass m(WD) because the temperature of the shock is directly proportional to the potential well of the WD. In magnetic systems, where accretion is funnelled to the magnetic poles of the WD, a strong standing shock is formed near the WD surface. Also in these systems, the X-ray flux and spectrum trace the accretion process and its rate, and allow estimates of m(WD).

In post-outburst novae, after the thermonuclear runaway the WD shrinks back to almost its previous radius, while the atmosphere is heated by residual shell burning. The effective temperature of hundreds of thousand K makes the WD a supersoft X-ray source, with luminosity close to the Eddington level of about 10^{38} erg s^{-1} and almost all the flux below 0.8 keV. In addition, also the shocked ejecta emit X-rays in the first post-outburst weeks, with a variety of phenomenological outcomes observable in X-rays.

2. Novae in outburst

For novae in outbursts, the projects described below were partially funded by the ASI-INAF program n. 2017-14-H-O, with a specific contribution to be used for collaborative travel and presentations at conferences. The funding was awarded for "high resolution grating spectra of novae in outburst and persistent supersoft X-ray sources".

2.1. Nova SMC 2016

Nova SMC 2016 was the most luminous nova known in the direction of the Magellanic Clouds. It turned into a very luminous SSS between days 16 and 28 after the optical maximum. We observed it with Chandra, the HRC-S camera, and the Low Energy Transmission Grating on 2016 November and 2017 January (days 39 and 88 after optical maximum), and with XMM-Newton on 2016 December (day 75).

We detected the compact WD spectrum as a luminous supersoft X-ray continuum with deep absorption features of carbon, nitrogen, magnesium, calcium, probably argon, and sulfur on day 39, and oxygen, nitrogen, and carbon on days 75 and 88, as shown in Fig. 1. The spectral features attributed to the WD atmosphere are all blueshifted, by about 1800 km s^{-1} on day 39 and up to 2100 km s^{-1} in the following observations. Spectral lines attributed to low-ionization potential transitions in the interstellar medium are also observed. Assuming the distance to the Small Magellanic Cloud, the bolometric luminosity exceeded the Eddington level for at least three months.

A preliminary analysis with atmospheric models indicates an effective temperature of around 700,000 K on day 39, peaking at the later dates in the 850,000-900,000 K range, as expected for a 1.25 $M_{\odot}$ WD. We suggest a possible classification as an oxygen-neon WD, but more precise modeling is needed to accurately determine the abundances. The X-ray light curves show a large, aperiodic flux variability, which is not associated with spectral variability. We detected red noise, but did not find periodic or quasiperiodic modulations. The results were published in Orio et al. (2018).

2.2. N LMC 2009

We examined four high-resolution reflection grating spectrometers (RGS) spectra of the February 2009 outburst of the luminous recurrent nova LMC 2009a. They were very complex and rich in intricate absorption and emission features. The continuum was consistent with a dominant component originating in the atmosphere of a shell burning WD with peak effective temperature between 810,000 K and a million K, and mass in the 1.2-1.4 $M_{\odot}$ range. A moderate blue shift of the absorption features of a few hundred km s^{-1} can be explained with a residual wind depleting the WD surface at a rate of about 10^{-8} $M_{\odot}$ yr^{-1}. The emission spectrum seems to be due to both photoionization and shock ionization in the ejecta. The supersoft X-ray flux was irregularly variable on time-scales of hours, with decreasing amplitude of the variability. We find that both the period and the amplitude of another, already known 33.3-s modulation varied within time-scales of hours.

We compared N LMC 2009a with other Magellanic Clouds novae, including four serendipitously discovered as supersoft X-ray sources (SSS) among 13 observed within 16 yr after the eruption. The new detected targets were much less luminous than expected: we suggest that they were partially obscured by the accretion disc. Lack of SSS detections in the Magellanic Clouds novae more than 5.5 yr after the eruption constrains the average duration of the nuclear burning phase. The results were published in Orio et al. (2021).

2.3. V407 Lupi

The 2016 eruption of nova V407 Lupi (ASASSN-16kt), was studied by me and my collaborators including optical, near-infrared, X-ray, and ultraviolet data from SALT, SMARTS, SOAR, Chandra, Swift, and XMM-Newton. Timing analysis of the multiwavelength light curves showed that, from 168 d

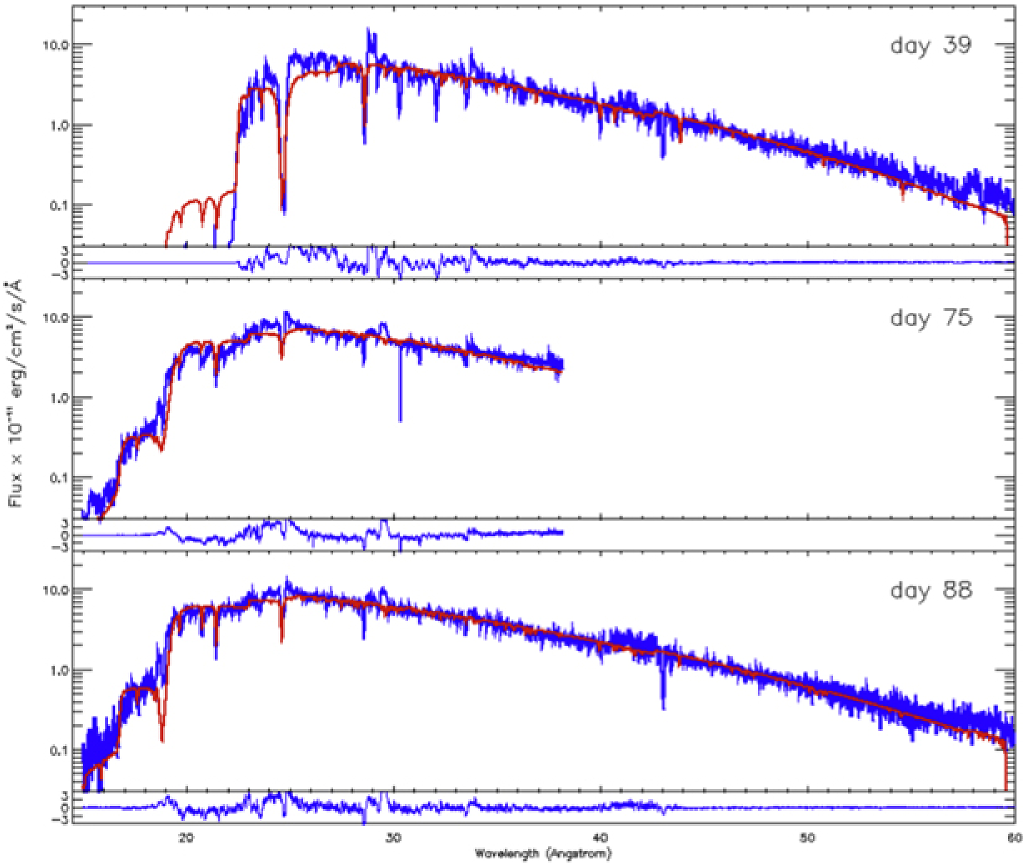

Fig. 1. In the top panels, the observed spectra of N SMC 2016 taken on days 39 and 88 with the Chandra HRC-S+LETG setup and on day 75 with the RGS of XMM-Newton are traced in blue for each date. The red lines show the XSPEC best fit with a TMAP model with log(g) = 9 and the parameters in Orio et al. (2018). The fit has been obtained by artificially moving the atmospheric absorption lines with respect to the original model in order to match the observed blueshift. For each spectrum, the lower panel shows, in linear scale, the residuals, namely the difference between the data and the model (From Orio et al. 2018).

post-eruption and for the duration of the X-ray supersoft source phase, two periods at 565 s and 3.57 h were detected. We suggested that these are the rotational period of the white dwarf and the orbital period of the binary, respectively, and that the system is likely to be an intermediate polar.

The optical light-curve decline was very fast (t_2 =2.9 d), suggesting that the white dwarf is likely massive (1.25 $M_\odot$). The optical spectra obtained during the X-ray supersoft source phase exhibit narrow, complex, and moving emission lines of He II, also characteristics of magnetic cataclysmic variables. The optical and X-ray data show evidence for accretion resumption while the X-ray supersoft source is still on, possibly extending its duration. The results were published in Aydi et al. (2018).

3. Accreting, quiescent sources

For my team's study of accreting sources in X-rays, the program described below were also partially funded by the ASI-INAF program n. 2017-14-H-O, also with a specific contribution for collaborative travel and presentations at conferences. Only for one of the sources a high resolution grating spectrum could be obtained, but the others were broad-band follow-ups of supersoft X-ray sources previously observed with the gratings.

3.1. Observations of accreting CVs

We analysed observations of novae V2491 Cyg and KT Eri about 9 yr post-outburst of the dwarf nova and post-nova candidate EY Cyg, and of a VY Scl variable. The first three objects were observed with XMM-Newton, KT Eri also with the Chandra ACIS-S camera, V794 Aql with the Chandra ACIS-S camera and High Energy Transmission Gratings. The two recent novae, similar in outburst amplitude and light curve, appear very different at quiescence. Assuming half of the gravitational energy is irradiated in X-rays, V2491 Cyg is accreting at $\dot{m}$=1.4 $\times 10^{-9}$ – 10^{-8} M$\odot$ yr^{-1}, while for KT Eri, $\dot{m} < 2 \times 10^{-10}$ M$\odot$ yr^{-1}.

V2491 Cyg shows signatures of a magnetized WD, specifically of an intermediate polar. A periodicity of 39 min, detected in outburst, was still measured and is likely due to WD rotation. EY Cyg is accreting at $\times 10^{-11}$ M$\odot$ yr^{-1}, a rate one magnitude lower than KT Eri, consistently with its U Gem outburst behaviour and its quiescent UV flux. The X-rays are modulated with the orbital period, despite the system's low inclination, probably due to the X-ray flux of the secondary. A period of 81 min is also detected, suggesting that it may also be an intermediate polar.

V794 Aql had low X-ray luminosity during an optically high state, about the same level as in a recent optically low state. Thus, we find no clear correlation between optical and X-ray luminosity: the accretion rate seems unstable and variable. The very hard X-ray spectrum indicates a massive WD. The results were published by my team, led by my student B. Sun, in Sun et al. (2020).

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