A Classical Nova, V2487 Oph 1998, Seen in X-rays Before and After Its Explosion

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Classical nova explosions are very energetic and frequent phenomena caused by explosive hydrogen burning on top of an accreting white dwarf. Observations of the recent nova V2487 Oph 1998 by the X-ray Multi-Mirror satellite (XMM-Newton) provide evidence that accretion (probably on a magnetic white dwarf) was reestablished as early as 2.7 years after the explosion. In addition, positional correlation with a source previously discovered by the Röntgen Satellite (ROSAT) in 1990 suggests that the site of a nova explosion had been seen in x-rays before the outburst.

Nova Ophiuchi 1998 (V2487 Oph) was discovered optically on June 15.561 UT (*1*), with a visual magnitude of 9.5, and was confirmed as a nova by spectral observations on 18 June 1998 (*2*). It was a very fast nova, with $t_2 \approx 6.3$ days and $t_3 \approx 9.5$ days (*3*) (where t_2 and t_3 are defined as the elapsed time to decreases of 2 and 3 magnitudes in its visual luminosity, respectively). We observed V2487 Oph twice with the XMM-Newton, on 25 February 2001 (986 days after outburst) and on 5 September 2001 (1178 days after outburst). Determining the duration of the post-outburst hydrogen-burning phase, which manifests itself through soft x-ray emission (*4–7*) (energies in the approximate range from 0.1 to 1 keV), is crucial for understanding the explosion mechanism and for quantifying the amount of mass that remains on the white dwarf surface after mass ejection. The duration of the post-outburst phase is related to residual nuclear burning and can be predicted theoretically from an estimate of the nuclear burning time scales (*8*), which range from 5.6×10^4 to 2×10^4 years (*9*) for white dwarf masses from 1.35 to 0.6 $M_\odot$ (where $M_\odot$ is solar mass). However, observations indicate a much shorter duration: Only 3 of 132 novae in our galaxy and in the Magellanic Clouds observed with ROSAT were detected as soft x-ray sources, and only one of these three was detected as late as 9 years after its explosion (*5, 10*). Turnoff times of novae have also been determined from ultraviolet observations (*11–13*), again yielding much shorter times than the nuclear burning time scales. The discrepancy between theoretical predictions and observed values may indicate larger than expected mass loss rates (i.e., through winds or common envelope interaction); however, a real understanding of the true mass loss mechanism and how it affects nova systems is still missing.

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V2487 Oph was detected with the XMM-Newton European Photon Imaging Camera (EPIC) instruments MOS1, MOS2, and PN during our two observations. Exposure time was about 6000 s, which was long enough to detect the source with the EPIC instruments but not with the Reflection Grating Spectrometer (RGS) instruments. The soft part of the spectrum (energies below ~1 keV) on day 1178 after outburst (Figs. 1 and 2) is compatible with blackbody emission of the whole white dwarf surface, which is hot because of residual nuclear burning. The blackbody temperature T_{BB} is 30 eV and the absorption, described by the hydrogen column density N_H, is 4×10^{21} cm^{-2}, which is slightly larger than the average

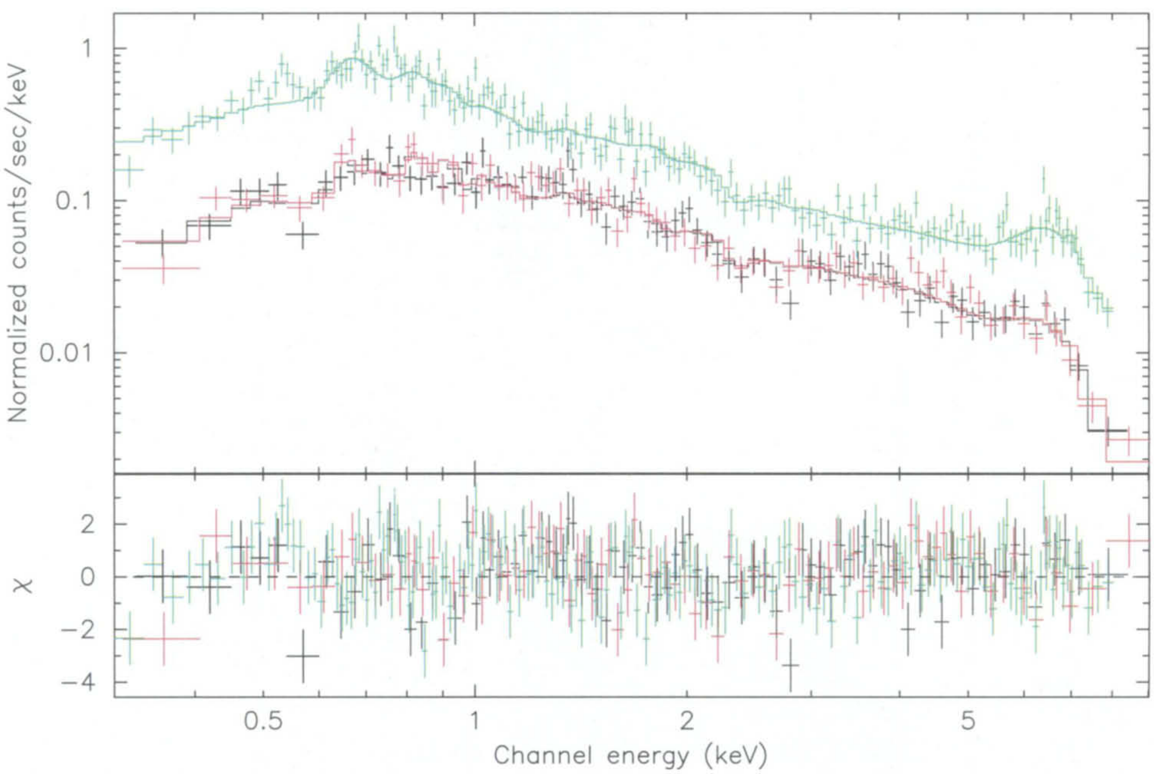

Fig. 1. Observed spectra of V2487 Oph. EPIC MOS1, MOS2, and PN data (second observation, done on 25 February 2001, 1178 days after outburst), binned to include at least 25 counts per bin, are displayed as crosses (black, red, and green, respectively). The channels below 0.3 keV and above 8.0 keV have been ignored because of inadequate instrumental response (*33*). Integration times for the three instruments were 7513, 7514, and 4680 s, giving 2479, 2511, and 5028 source counts, respectively, in the range 0.3 to 8.0 keV. The observed count rates were 0.325 ± 0.007, 0.327 ± 0.007, and 1.058 ± 0.016 counts s^{-1}, respectively. Continuous lines show the models that best fit the data from the three instruments simultaneously. The lower panel displays the residuals between the models and the data in units of σ. The reduced χ^2 of the fit is $\chi_\nu^2 = 1.18$.

interstellar absorption in the direction of the source (*14*) (2×10^{21} cm^{-2}), probably as a consequence of extra absorption in the accretion column. For a fixed $T_{BB} = 30$ eV (*15*), the bolometric luminosity of the blackbody emission is 2.9 ($\pm$0.7) $\times$ $(d/10)^2 \times 10^{37}$ erg s^{-1} (where d is the distance to the source in kpc), with an emission surface of radius 1.8 ($\pm$0.2) $\times$ $(d/10) \times 10^9$ cm. The distance to V2487 Oph is very uncertain, ranging between 8 and 27 kpc (*16*), thus yielding a range of luminosities and radii. The blackbody bolometric luminosity, 0.2×10^{38} to 2.1×10^{38} erg s^{-1}, is close to the Eddington luminosity for a 1.2 $M_\odot$ white dwarf ($\sim 10^{38}$ erg s^{-1}), and the white dwarf photospheric radius, 1.4×10^9 to 4.9×10^9 cm, agrees with its expected value during the constant bolometric luminosity phase of novae [$4.75 \times 10^{10}(10^5$ K$/T_{BB})^2$ cm for a 1.2 $M_\odot$ white dwarf (*17*)]. Model atmospheres of hot white dwarfs would be more appropriate than blackbodies to fit the soft x-rays (*18, 19*), but a more accurate model with a hot white dwarf atmosphere would not improve the parameters of the fit, because there are not enough counts in all of the relevant energy ranges and because the lowest available energy is 0.3 keV. A second interpretation of the soft component is that part of the surface of the white dwarf has been heated by the hard x-ray radiation from the accretion flow. Only data at energies below 0.3 keV, which we do not have, could resolve this issue. If the soft x-rays did originate in the hot white dwarf photosphere because of residual burning, this would be a relatively unique case where the turnoff time of the nuclear burning is longer than 3 years (*20*), consistent with the theoretical nuclear burning time scales (*9*).

The hard component can be fit with a two-temperature plasma model [MEKAL (*21*) model from XSPEC (*22*)], with T_{low} = 0.2 keV and $T_{high} \geq 48$ keV, indicating the existence of shocked gas as a consequence of an accretion flow (*23*). In addition, there is a fluorescent Fe K_α line emission at 6.4 keV, indicating the possible existence of reflection (either on an accretion disk or on the white dwarf surface). This kind of emission has been observed with the Advanced Satellite for Cosmology and Astrophysics (ASCA) in some cataclysmic variables [e.g., in the intermediate polars EX Hya and AO Pisc (*24–26*)], but the hard x-ray spectrum of V2487 Oph is less steep and thus has a higher plasma temperature than EX Hya and AO Pisc. This higher temperature may be the consequence of accretion onto a massive white dwarf, as suggested by the optical light curve of V2487 Oph (*27*). The luminosity in the energy range from 0.3 to 8.0 keV is $5 \times (d/10)^2 \times 10^{34}$ erg s^{-1}. We have compared the two observations (2.7 and 3.2 years after outburst) and checked that there were not relevant changes, either in best-fit model parameters or in fluxes. This finding also supports the resumption of accretion as the origin of the emission. The resumption of accretion so soon after outburst is unexpected, because mass ejection associated with nova explosions should inhibit accretion over time scales of a few years.

The strength of the magnetic field of the V2487 Oph white dwarf, and therefore the type of cataclysmic variable (e.g., nonmagnetic, intermediate polar, or polar), cannot be determined with our data. Our data do not show any evident periodicity related with the rotation of the white dwarf and its orbital motion, and there are no optical data available to verify it. The large distance to the system makes it difficult to obtain information from observations at optical or ultraviolet wavelengths. However, the large luminosity and the slope of the hard x-ray spectral component favor a magnetic cataclysmic variable. The presence of a magnetic field would hinder the buildup of the accretion disk and the development of the thermonuclear runaway needed to power a nova outburst (*28*), but other novae (such as V1500 Cyg, DQ Her, and GK Per) have also exploded on magnetic white dwarfs.

V2487 Oph is in the same position as the x-ray source 1RXS J173200.0-1934, detected by the RASS (ROSAT All-Sky Survey) in September 1990 (*29*). The optical emission from V2487 Oph was within the 16–arc sec ROSAT error box of 1RXS J173200.0-1934 (*1*), but now XMM-Newton has provided a stronger constraint, because the positions of

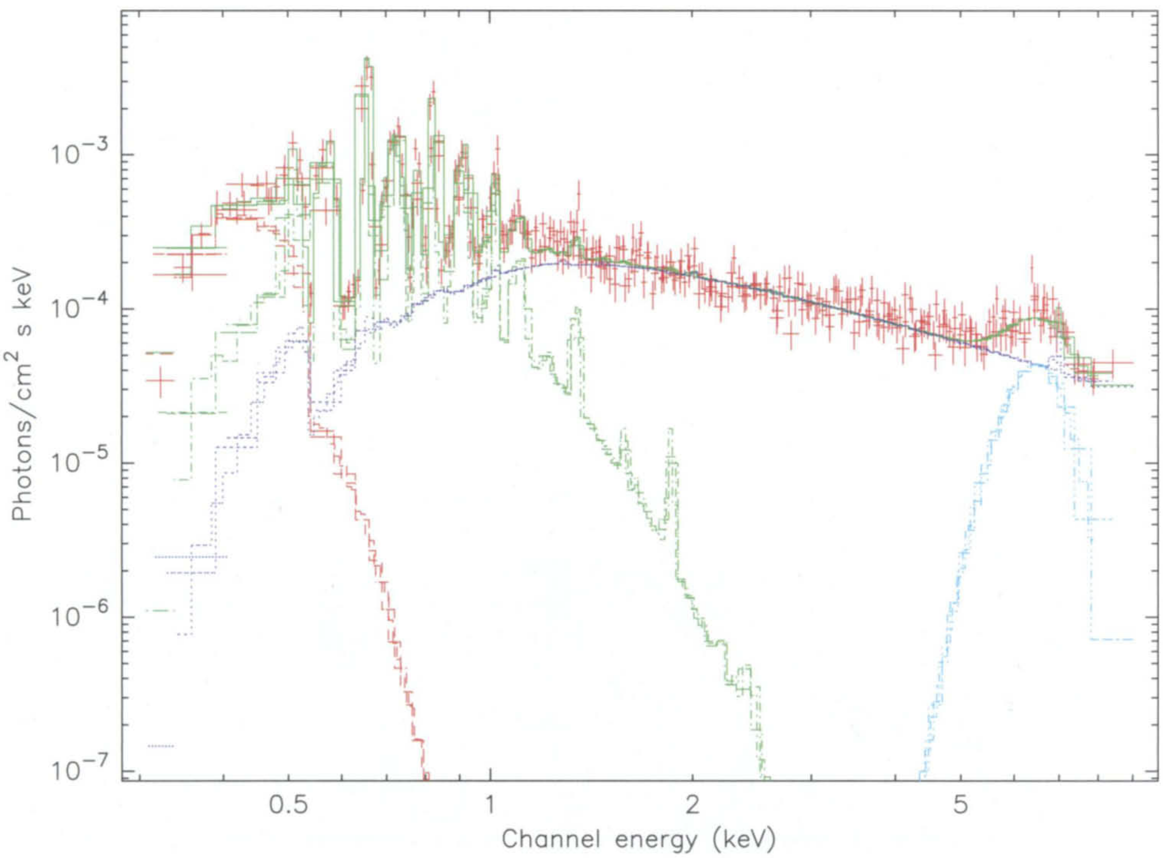

Fig. 2. Unfolded spectrum and best-fit model (*15*) for the same observation shown in Fig. 1. Contributions to the model of the various additive components are also shown: blackbody (red curve spanning the low energies), low-T plasma (green), high-T plasma (dark blue), Gaussian line (light blue), and total (red curve spanning the energy range). An Fe K_α fluorescent line at 6.4 keV (simulated with a Gaussian) is needed, in addition to the two-temperature thermal plasma [from the MEKAL (*21*) code] and the blackbody, in order to fit the excess at those energies.

V2487 Oph and 1RXS J173200.0-1934 are closer than the angular resolution of the XMM-Newton instruments (i.e., they are less than ~6 arc sec apart). The ROSAT spectrum (exposure for 462.7 s, with counts in the energy range between 0.75 and 2.4 keV) is compatible with the XMM-Newton spectrum. The 1RXS J173200.0-1934 flux, 3.3×10^{-13} to 8.9×10^{-13} erg cm^{-2} s^{-1}, from the RASS bright source catalog (1RXS-B) is consistent with that from XMM-Newton (9.4×10^{-13} erg cm^{-2} s^{-1}). The similar fluxes indicate that 1RXS J173200.0-1934 and V2487 Oph might be the same object. Therefore, the site of a classical nova may have been seen before the nova explosion itself (as early as 8 years before it), thanks to the x-rays emitted in the accretion flow. This supports the cataclysmic variable scenario for nova explosions.

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8. The nuclear burning time scale is defined as the time needed to burn by nuclear reactions (of hydrogen, in novae) all of the remaining envelope. Its value is about 400 years for an envelope mass of 10^{-4} $M_{\odot}$ and a luminosity of 2×10^4 $L_{\odot}$ and it is proportional to mass and inversely proportional to luminosity.
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15. Parameters of the model best fitting the spectra of V2487 Oph follow, with 1σ uncertainties. Low-T MEKAL: kT (keV) = 0.22 ± 0.01, emission measure $(3.1^{+0.3}_{-0.2}) \times 10^2$ $(d/10\ kpc)^2 \times 10^{55}$ cm^{-3}; high-T MEKAL: kT (keV) ≥ 48, emission measure 3.5 (±0.9) $\times 10^2$ $(d/10\ kpc)^2 \times 10^{55}$ cm^{-3}; Gaussian line: E_{line} (keV) = 6.5 ± 0.1, σ_{line} (keV) = 0.6 ± 0.1, F_{line} (photons cm^{-2} s^{-1}) = $(6.6^{+1.3}_{-1.1}) \times 10^{-5}$. Blackbody temperature and absorption N_H have been fixed (30 eV and 4×10^{21} cm^{-2}, respectively). The emission measure of the MEKAL plasma model is defined as $\int n_e n_H dV$ (where n_e and n_H are the electron and hydrogen densities, in cm^{-3}, and V is the volume of the emitting plasma). The bolometric flux of the blackbody component is 2.9 (±0.7) $\times$ $(d/10\ kpc)^2 \times 10^{37}$ erg s^{-1}, and the total absorbed flux, in the 0.3 to 8.0 keV range, is 4.6×10^{-12} erg cm^{-2} s^{-1}, yielding an x-ray luminosity of $5.2 \times (d/10\ kpc)^2 \times 10^{34}$ erg s^{-1}. The reduced χ^2 of the fit is $\chi^2_\nu = 1.18$, with number of degrees of freedom $\nu = 340$.
16. The distance to V2487 Oph derived by Lynch *et al.* (*30*) was 27 ± 3 kpc. They used an empirical $M_V^{max}(t_2)$ relation to obtain M_V^{max} (absolute visual magnitude at maximum), the apparent visual magnitude at maximum m_V^{max} from observations (*1*), and the visual extinction, A_V = 1.16 ± 0.24 mag; they obtained A_V from the color excess E(B-V) = 0.38 ± 0.08 obtained from the observed OI λ8446 and λ11287 near-infrared lines. The distance 27 kpc is very large, and its determination should be taken with caution. It is probable that for very fast novae (such as V2487 Oph), the real visual maximum is missed by observers and therefore the true m_V^{max} is much brighter. The faintness of the nova (m_V = 9.5 at discovery) further prevents its discovery at maximum. An estimation of m_V^{max} follows from extrapolation of the visual light curve back in time to the prediscovery data or to some reasonable m_V^{max}, with a slope dictated by t_2 or t_3 (*31*). This exercise yields m_V^{max} in the range 6.8 to 9.5, leading to a distance between 8 and 27 kpc (for M_V^{max} = −8.8 and A_V = 1.16). Another source of uncertainty is the empirical $M_V^{max}(t_2)$ relation, which should not necessarily be valid for all the systems (although it is generally accepted as such).
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20. The nova GQ Mus has the longest turnoff time observed to date, 9 years (*5*), and nova LMC 1995 was still emitting soft x-rays in 2000 (*32*). These two novae and V2487 Oph are the only ones to date with observed (through x-rays) turnoff times longer than 3 years.
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34. This work is based on observations obtained with XMM-Newton, a European Space Agency (ESA) science mission with instruments and contributions directly funded by the ESA member states and by NASA. Supported in part by the Ministerio de Ciencia y Tecnología.

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Magnetic Superstructure in the Two-Dimensional Quantum Antiferromagnet $SrCu_2(BO_3)_2$

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We report the observation of magnetic superstructure in a magnetization plateau state of $SrCu_2(BO_3)_2$, a frustrated quasi–two-dimensional quantum spin system. The Cu and B nuclear magnetic resonance (NMR) spectra at 35 millikelvin indicate an apparently discontinuous phase transition from uniform magnetization to a modulated superstructure near 27 tesla, above which a magnetization plateau at 1/8 of the full saturation has been observed. Comparison of the Cu NMR spectrum and the theoretical analysis of a Heisenberg spin model demonstrates the crystallization of itinerant triplets in the plateau phase within a large rhomboid unit cell (16 spins per layer) showing oscillations of the spin polarization. Thus, we are now in possession of an interesting model system to study a localization transition of strongly interacting quantum particles.

The competition between itinerancy favored by kinetic energy and localization favored by repulsive interactions is a fundamental aspect of many-body quantum systems, of which the Mott (metal-insulator) transition is an example (*1*). Similar phenomena may occur for the spin degrees of freedom of certain magnetic insulators, known as spin liquids, in which the ground state is a singlet separated from triplet excitations by a finite energy gap Δ. Transition metal oxides exhibiting this kind of physics have been actively studied in an effort to understand the more complex physics of high-temperature superconductors [e.g., (*2*)], a good example being spin ladders (*3*). In such systems, a magnetic field H_c =

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