V5116 SAGITTARI, AN ECLIPSING SUPERSOFT POSTOUTBURST NOVA?

G. Sala,1 M. Hernanz,2 C. Ferri,2 and J. Greiner1

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ABSTRACT

V5116 Sgr (Nova Sgr 2005 No. 2), discovered on 2005 July 4, was observed with XMM-Newton in 2007 March, 20 months after the optical outburst. The X-ray spectrum shows that the nova had evolved to a pure supersoft X-ray source, with no significant emission at energies above 1 keV. The X-ray light curve shows abrupt decreases and increases of the flux by a factor ~8. It is consistent with a periodicity of 2.97 hr, the orbital period suggested by Dobrotka and coworkers, although the observation lasted just a little more than a whole period. We estimate the distance to V5116 Sgr to be 11 ± 3 kpc. A simple blackbody model does not fit correctly the EPIC spectra, with $\chi^2 > 4$. In contrast, ONe-rich white dwarf atmosphere models provide a good fit, with $N_H = (1.3 \pm 0.1) \times 10^{21}$ cm$^{-2}$, $T = (6.1 \pm 0.1) \times 10^9$ K, and $L = (3.9 \pm 0.8) \times 10^{37} (D/10$ kpc)$^2$ ergs s$^{-1}$ (during the high-flux periods). This is consistent with residual hydrogen burning in the white dwarf envelope. The white dwarf atmosphere temperature is the same both in the low- and the high-flux periods, ruling out an intrinsic variation of the X-ray source as the origin of the flux changes. We speculate that the X-ray light curve may result from a partial coverage by an asymmetric accretion disk in a high-inclination system.

Subject headings: binaries: close — novae, cataclysmic variables — stars: individual (V5116 Sagittarii) — X-rays: binaries — X-rays: individual (V5116 Sagittarii)

Online material: color figures

1. INTRODUCTION

Classical novae occur in close binary systems of the cataclysmic variable type, when a thermonuclear runaway results in explosive hydrogen burning on the accreting white dwarf (WD). It is theoretically predicted that novae return to hydrostatic equilibrium after the ejection of a fraction of the accreted envelope. Soft X-ray emission arises in some postoutburst novae as a consequence of residual hydrogen burning on top of the WD. As the envelope mass is depleted, the photospheric radius decreases at constant bolometric luminosity (close to the Eddington value) with an increasing effective temperature. This leads to a hardening of the spectrum from optical through UV, extreme UV, and finally soft X-rays, with the postoutburst nova emitting as a supersoft source (SSS) with a hot WD atmosphere spectrum. The duration of this SSS is related to the nuclear burning timescale of the remaining H-rich envelope and depends, among other factors, on the WD mass (Tuchman & Truran 1998; Sala & Hernanz 2005a, 2005b).

All postoutburst novae are expected to undergo SSS emitting phase, provided a H-rich envelope is left. Nevertheless, the number and duration of SSS states observed in Galactic novae is small. In a systematic search for the X-ray emission from novae in the ROSAT archive, Orio et al. (2001) found only three SSS novae from a total of 39 novae observed less than 10 years after the outburst (GQ Mus, V1974 Cyg, N LMC 1995). After the ROSAT era, observations by Beppo-SAX and Chandra revealed SSS X-ray emission for some more postoutburst novae: V382 Vel (Orio et al. 2002; Burwitz et al. 2002), V1494 Aql, with a puzzling light curve showing a short burst and oscillations (Drake et al. 2003), and V4743 Sgr, also with a very variable light curve (Ness et al. 2003; Petz et al. 2005). The SSS phase of the recurrent nova RS Oph in the 2006 outburst was monitored with Swift, XMM-Newton, and Chandra, and the end of the SSS state occurred less than 100 days after outburst (Bode et al. 2006; Hachisu et al. 2007). XMM-Newton has contributed with some more observations of novae. Nova LMC 1995 showed the SSS emission 5 years after outburst (Orio et al. 2003). Other postoutburst novae were detected with a harder spectrum associated to the expanding ejecta, as Nova LMC 2000 (Greiner et al. 2003) and V4633 Sgr (Hernanz & Sala 2007), or reestablished accretion flow (V2487 Oph; Hernanz & Sala 2002; Ferri et al. 2007). More recently, the SSS XSSM1.1 J070542.7–381442 was identified as a nova (Read et al. 2007a, 2007b; Torres et al. 2007).

X-ray observations of the central area of M31, with its moderate absorption, offer a good chance to monitor the SSS phase of novae: Pietsch et al. (2005) reported 21 X-ray counterparts for novae in M31—mostly identified as SSSs by their hardness ratios—and two in M33. Following that work, XMM-Newton and Chandra monitoring of M31 between 2004 July and 2005 February provided the detection of 11 out of 34 novae within a year after optical outburst (Pietsch et al. 2007). This suggests that the low fraction of SSSs found by Orio et al. (2001) was due to selection effects and/or too poor sampling.

X-ray observations of postoutburst novae provide crucial information: soft X-rays yield a unique insight into the remaining burning envelope on top of the WD, while hard X-rays reveal shocks in the nova ejecta. The properties of “quiescent novae,” once they have turned off and once accretion is reestablished (which can occur before or after the turnover), are revealed both in hard and soft X-rays; they emit then as “standard” cataclysmic variables. In view of the scarcity of objects observed and the diversity of behaviors detected, only the monitoring of as many novae as possible, with large sensitivity and spectral resolution (as those offered by XMM-Newton and Chandra) can help to understand postoutburst novae.

V5116 Sgr (Nova Sgr 2005 No. 2) was one of the targets included in our X-ray monitoring program of postoutburst Galactic novae with XMM-Newton. It was discovered by Liller (2005) on 2005 July 4.049 UT, with magnitude ~8.0, rising to mag 7.2 on July 5.085. The expansion velocity derived from...
Fig. 1.—V5116 Sgr X-ray and UV light curves during the XMM-Newton observation on 2007 March 5. Time units are TJD (JD − 2,440,000.5) and the time bin is 50 s. X-ray light curves are background subtracted. (a) EPIC MOS1 (black), MOS2 (red), and EPIC-pn (green) count rates, in the 0.2–1.0 keV energy range, normalized to 10 counts s\(^{-1}\) (see text for details). (b, c) EPIC MOS1, MOS2, and pn count rates in the bands 0.2–0.4 keV and 0.4–0.6 keV. (d) Hardness ratio for the three EPIC cameras. (e) OM U-band instrumental magnitudes for V5116 Sgr and for two comparison stars in the OM FOV. [See the electronic edition of the Journal for a color version of this figure.]

a sharp P Cygni profile detected in a spectrum taken on July 5.099 was ≃ 1300 km s\(^{-1}\). IR spectroscopy on July 15 showed emission lines with FWHM ≃ 2200 km s\(^{-1}\) (Russell et al. 2005). Photometric observations obtained during 13 nights in the period 2006 August–October show the optical light curve modulated with a period of 2.9712 ± 0.0024 hr (Dobrotka et al. 2008), which the authors interpret as the orbital period. They determined a first fit with a blackbody indicated \(T \sim 4.5 \times 10^5\) K. More recently, a 35 ks Chandra spectrum obtained on 2007 August 28 was fit with a WD atmospheric model with \(N_\text{H} = 4.3 \times 10^{21}\) cm\(^{-2}\) and \(T = 4.65 \times 10^5\) K (Nelson & Orio 2007).

Here we report on the X-ray light curve and broadband spectra of V5116 Sgr as observed by XMM-Newton in 2007 March, 609 days after outburst.

2. OBSERVATIONS AND DATA ANALYSIS

V5116 Sgr was observed with XMM-Newton (Jansen et al. 2001) on 2007 March 5 (Sala et al. 2007; observation ID: 0405600201, PI: Hernandez). The exposure times were 12.7 ks for the European Photon Imaging Cameras (EPIC) MOS1 and MOS2 (Turner et al. 2001), 8.9 ks for the EPIC-pn (Strüder et al. 2001), 12.9 ks for the Reflection Grating Spectrometers (RGS; den Herder et al. 2001), and 9.2 ks for the Optical Monitor with U filter (OM; Mason et al. 2001).

The observation was affected by an X-ray storm, which produced moderate background in the EPIC cameras for most of the exposure time. Fortunately enough, our target was at least a factor 10 brighter than the background. In addition, the source spectrum is very soft and little affected by solar flares. We therefore do not exclude any time interval of our exposures, but we pay special attention to the background subtraction of both spectra and light curves. Data were reduced using the XMM-Newton Science Analysis System (SAS 7.1.0). Standard procedures described in the SAS documentation (Loiseau 2005; Snowden et al. 2004) were followed. We applied flag filter \(\text{FLAG} = 0\), and only events with pattern smaller than 12 (MOS) and 4 (pn), were selected for the analysis of the EPIC data.

The high flux of the source resulted in pileup in the three EPIC cameras (used in large partial window mode). We minimize the pileup effect by extracting both spectra and light curves from annular regions that exclude the central, piled-up pixels. We determined the optimal extraction region by extracting the source spectra using annular regions with increasing inner radius until we found that the pileup effect was minimized, keeping a reasonable signal to noise. For the extraction of the source light curve we use an annular region with inner and outer radii 25′′ and 38′′ (for pn), and 10′′ and 80′′ (for MOS), respectively, for the whole exposure time. Background for the MOS cameras was extracted from an annulus region centered on the source, with an external radius of 140′′ and an internal radius of 115′′. In the case of the pn, the CCD where the source was detected had no large area without source photons, so we used two box regions in different CCDs, free of sources, for the background light curve determination. Nevertheless, we could not extract a spectrum completely free of pileup for the pn camera and we consider only the MOS cameras for broadband spectral analysis. We increased the statistics for the MOS spectra during the low-flux periods by reducing the inner radii of the source extraction regions down to 5′′. For the high-flux state we increased the inner radii to 40′′ to avoid pileup as much as possible. We have also reduced the RGS data, not affected by pileup, using the standard procedures. We also find two well-differentiated states, coincident in time with the high- and low-rate periods of the EPIC cameras. The RGS spectra, while compatible with the broadband models used to fit the MOS spectra in this Letter, show a number of absorption/emission features that require a detailed spectral analysis, to be presented in a separate work.

3. LIGHT CURVE

Figure 1a shows the background-subtracted light curves of the three EPIC cameras in the 0.2–1.0 keV band. There is no significant flux above 1.0 keV. EPIC-pn experienced full scientific buffer at the beginning of the observation, and started to collect data later than the other instruments. The Y-axis in the EPIC light curves is only in relative units, since the annulus extraction regions used do not provide the total source rate. For comparison purposes, the 0.2–1.0 keV count rates have been renormalized for the three EPIC cameras to 10 counts s\(^{-1}\) (close to the actual maximum count rate using the annulus extraction region, 10.9 counts s\(^{-1}\) for MOS1, 10.2 counts s\(^{-1}\) for MOS2, and 13.1 counts s\(^{-1}\) in pn).

The X-ray light curve shows clearly two states: a high-flux
state, during the first 600 s, and again starting 8300 s after the start of the MOS exposures and lasting for 3000 s; and a low-flux state between 600 and 8300 s, and during the last 1200 s of the observation. A small flare is observed during the last low-flux period. The count rate during the low-flux period between 600 and 8300 s does not show significant variations (25% rms variability). In contrast, the count rate during the high-state shows flaring activity. If the first decline after the initial high-flux period corresponds to the end of a 3 ks burst like the one starting at 8300 s, this would point to a periodicity in the X-ray light curve of 10.5–10.7 ks (2.92–2.97 hr). This is consistent with the periodicity found in the optical light curve in 2006 August–October by Dobrotka et al. (2008) (2.9712 ± 0.0024 hr), which was suggested by the authors to be the orbital period.

Figures 1b and 1c show the count rates in two energy bands, 0.2–0.4 keV and 0.4–0.6 keV, respectively, for the three EPIC cameras. EPIC-pn shows a softer spectral distribution than the two MOS cameras, especially during the high-flux state. This indicates that pileup is still affecting the EPIC-pn data (and therefore we do not use them in the spectral analysis). The source is very soft with low signal above 0.6 keV, insufficient to define a third energy band above 0.6 keV. The hardness ratio (Fig. 1d) indicates that there are no significant variations of the spectral properties during the whole observational period, even when the rate is increasing by a factor 8–10 in the high-flux phases.

Figure 1e shows the light curve of the OM exposures in the U band in instrumental magnitudes. The light curve of two stars in the field of view close to V5116 Sgr are shown for comparison. The OM light curve is compatible with the 2.97 hr periodicity observed by Dobrotka et al. (2008) but its minimum is not correlated either with the maximum or the minimum in X-rays. This points to different origins for the X-ray and UV emission.

4. SPECTRAL ANALYSIS

The X-Ray Spectral Fitting Package (XSPEC 11.3; Arnaud & Dorman 2003) was used for spectral analysis. We used only MOS data for the spectral analysis, since EPIC-pn is too affected by pileup. Even for the EPIC-MOS cameras, some residual pileup is likely responsible for a component at energies twice the maximum of the emission, i.e., 0.8–1.0 keV, caused by double events at 0.4–0.5 keV counted as single photons with twice the energy. These lost photons are only a small fraction of the total at the maximum of emission (and cause a small effect in the 0.3–0.5 keV band), but they contribute notably at 0.8–1.0 keV, where the intrinsic flux of the source is very small, if any. This implies that we can trust the spectral analysis only up to 0.7 keV and we cannot provide any constraint on a possible reestablished accretion disk. In our spectral fits, we use the phabs model with Wilms et al. (2000) abundances for the foreground absorption.

Figure 2 shows the MOS1 and MOS2 spectra during the low-flux period. A first attempt to fit a simple absorbed blackbody model to the data yields an unacceptable fit, with $\chi^2 > 4$. Therefore we used MacDonald & Vennes (1991) WD atmosphere emission models, kindly provided by Jim MacDonald, and built tables to be read as external models in XSPEC. Previous studies have shown the importance of including WD atmosphere models instead of simple blackbodies for a correct broadband spectral analysis of novae in the SSS phase (Balman et al. 1998; Balman & Krautter 2001; Orio & Greiner 1999).

![XMM-Newton MOS1 (black) and MOS2 (red) spectra of V5116 Sgr. (a) Low-flux spectra fit with a CO WD atmosphere model. (b) Low-flux spectra fit with an ONe WD atmosphere model. (c) High-flux MOS1 and MOS2 spectra fit with an ONe WD atmosphere model. [See the electronic edition of the Journal for a color version of this figure.]](image)

Two sets of models are available, corresponding to CO and ONe compositions of the WD. As shown in Figure 2a, CO atmosphere models do not fit the data well. The main difference between the two types of nova atmospheres at these temperatures is the hard energy tail of ONe models, which is suppressed in CO models due to the C ionization edges (C v at ~0.4 keV and C vi at ~0.5 keV). The best fit is obtained with the ONe models (Fig. 2b), with $N_H = (1.3 \pm 0.1) \times 10^{21}$ cm$^{-2}$, $T = (6.1 \pm 0.1) \times 10^5$ K, and a luminosity (determined from the normalization constant) $L = (4.9 \pm 0.6) \times 10^{38} (D/10$ kpc)$^2$ erg s$^{-1}$. The observed $N_H$ is consistent with the average interstellar absorption toward the source (1.34 $\times 10^{21}$ cm$^{-2}$; Kalberla et al. 2005).

The spectrum during the high-flux state (Fig. 2c) is well fit with the same ONe WD atmosphere model, with $N_H = (1.5 \pm 0.2) \times 10^{21}$ cm$^{-2}$, $T = (6.1 \pm 0.1) \times 10^5$ K, and a normalization constant a factor ~8 larger, corresponding to a luminosity $L = (3.9 \pm 0.8) \times 10^{39} (D/10$ kpc)$^2$ ergs s$^{-1}$.

5. DISCUSSION

V5116 Sgr was detected as a bright SSS by XMM-Newton 20 months after the nova outburst. The temperature of the WD atmosphere indicates that residual hydrogen burning is occur-
ring in the WD envelope. To further confirm the origin of the emission and determine the size of the emitting surface, we need an estimation of the distance. Fortunately enough, the time and magnitude at maximum are quite well determined for V5116 Sgr, with a premaximum observation only 24 hr before the maximum. Liller (2005) reported $m_v = 7.15$ at maximum, and $t_2$ (time required to decline 2 magnitudes from maximum) was $6.5 \pm 1.0$ days (Dobrotka et al. 2008). Using the empirical relation for novae between $M_v$ and $t_2$ (Della Valle & Livio 1995) the observed $t_2$ implies an absolute magnitude at maximum $M_v = (-8.8 \pm 0.4)$ (we add a 5% error to account for the scatter in the $M_v$-$t_2$ relation). The photometry at maximum indicates $B - V = +0.48$ (Gilmore & Kilmartin 2005), and for novae at maximum, intrinsic $B - V = 0.23 \pm 0.06$ (van den Bergh & Younger 1987). This implies $A_v = 3.1 E_{B-V} = 0.8 \pm 0.2$. With all this, we estimate the distance to V5116 Sgr to be $d = 11 \pm 3$ kpc. For simplicity, we scale the distance-dependent parameters to 10 kpc. It is worth noting that the $N_H$ obtained from our fits indicates $A_v = 0.7$ ($N_H = 5.9 \times 10^{22} E_{B-V}$ cm$^{-2}$; Zombeck 2007), consistent with the value obtained from the observed colors.

The luminosity during the high-flux periods, together with the atmosphere temperature, indicate a radius of the emitting object $R = (6.2 \pm 0.9) \times 10^4 (D/10$ kpc). This corresponds to the whole WD surface emitting during the high-flux periods and supports residual H-burning as the origin of the SSS emission, rather than any feature related to the accretion stream (boundary layer, hot spot, or hot accretion poles).

The most remarkable feature in V5116 Sgr is the SSS light curve. Although the observation lasted just a bit longer than an orbital period, we obtain a period compatible with the orbital period of 2.97 hr found by Dobrotka et al. (2008). The fact that the temperature is the same for both the high- and the low-flux phases indicates that the change in flux cannot be caused by an intrinsic change in the H-burning envelope. The luminosity in the high-flux periods also indicates that the whole WD is visible in this state. The decrease by a factor $\sim 8$ in the flux could be caused by a partial eclipse of the WD. The long duration of the low-flux phase and short duration of the high-flux phase cannot be reconciled with a partial eclipse by the secondary star. Alternatively, some asymmetric accretion disk could do the job, being responsible for a partial eclipse during most of the orbital period, with a 3 ks window during which the whole WD would be visible. Since no change is observed in the hydrogen absorption column and it is compatible with the average interstellar value both in the low- and the high-flux spectra, the portion of accretion disk producing the partial eclipse should be optically thick to the soft X-rays. In the particular case of V5116 Sgr, we have checked that an absorbing column of $N_H > 2 \times 10^{22}$ cm$^{-2}$ would make it completely opaque to the observed SSS emission. Longer X-ray observations covering at least two periods together with a good timing with the OM camera would be required to disentangle the origin of the X-ray light curve behavior.

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