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THE FIRST RESOLVED AND DETECTED CLASSICAL NOVA SHELL IN X-RAYS: THE SHELL OF NOVA PERSEI 1901

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ABSTRACT

We present the *ROSAT* High-Resolution Imager data of the first resolved and detected classical nova shell in the X-ray wavelengths: the shell of Nova Persei 1901. We find that the X-ray nebula is composed of knots/clumps and has an elliptical shape with a total count rate of about 0.01 ± 0.001 counts s^{-1}. We estimate that the spectrum is of thermal origin with a luminosity of $\sim 8.0 \times 10^{31}$ ergs s^{-1} and an X-ray temperature of $\sim 2.0 \times 10^{6}$ K in the 0.1–2.4 keV energy range. The knots/clumps are a result of fragmentation and condensation in the postshock region. The estimated electron density in the knots/clumps is about $10.0\ \mathrm{cm}^{-3} \leq n_e \leq 70.0\ \mathrm{cm}^{-3}$. We suggest that the detected X-ray nebula could also be the reverse shock zone. This detection sheds light into one of the most poorly understood stages of the classical nova evolution.

Subject headings: binaries: close — novae, cataclysmic variables — radiation mechanisms: thermal — stars: individual (GK Persei) — X-rays: stars

1. INTRODUCTION

Cataclysmic variables (CVs) are interacting binary stellar systems containing a main-sequence secondary and a collapsed primary component, a white dwarf (Warner 1995). Classical novae are a subset of CVs in which an outburst on the surface of the white dwarf due to a thermonuclear runaway in the accreted material results in the ejection of about 10^{-4} to $10^{-7}\ M_{\odot}$ of material at velocities up to several thousand kilometers per second (Gallagher & Starrfield 1978; Shara 1989; Livio 1994). The old nova Persei 1901 (GK Per) is the first bright classical nova of the twentieth century. It has a high ejection velocity, $V_{\rm eject} \simeq 1200$ km s^{-1} (Pottasch 1959), and an ejected mass $M_{\rm eject} \simeq 7 \times 10^{-5}\ M_{\odot}$ (McLaughlin 1960).

The optical images of the expanding ejecta obtained over several decades show that the shell is composed of a series of knots and blobs with dimensions 103×90 arcsec^2 obtained in 1993 (Seaquist et al. 1989; Slavin, O'Brien, & Dunlop 1995). The bulk of emission arises in the southwestern quadrant with evident flattening of the shell, indicating interaction between the nova ejecta and the ambient gas. The remnant is detected with the Very Large Array (VLA) as a nonthermal, polarized radio source with a spectral index -0.67 at 1.5 and 4.9 GHz, indicating the existence of shocked circumstellar material (Reynolds & Chevalier 1984). The *Infrared Astronomical Satellite* (*IRAS*) observations at 60 and 100 μm reveal an emission region extending around the nova out to 6 pc (symmetrically), interpreted as a fossil planetary nebula associated with the binary (Bode et al. 1987b). Recent observations of this nebulosity in the optical wavelengths strongly suggest that it is produced during the quiescent mass-loss phase of the central binary, since the mass-loss rate may be substantially enhanced in this system because of the evolved nature of the secondary (Tweedy 1995). Recent IR observations also indicate that the IR emission within 17′ of the source is of material originating from the secondary star (Dougherty et al. 1996). Considering the above characteristics, it is widely believed that the GK Per nebula behaves more like a young supernova remnant in the pre-Sedov phase.

In general, the electron temperatures as measured from the optical and ultraviolet wavelength observations suggest the existence of either hot ($T_e > 10^4$ K) or cold ($T_e \leq 10^4$ K) nova shells (Williams 1982). Some of the old nova shells have been found to decelerate in time, such as DQ Her, GK Per, V603 Aql, T Pyx, and V476 Cyg, suggesting the existence of circumstellar interaction (Duerbeck 1987). Despite the fact that none of the old classical novae remnants have been detected in the X-rays, X-ray emission originating from hot-shocked gas has been detected from classical nova shells during the outburst stage as *inferred* from their X-ray spectrum (Balman, Krautter, & Ögelman 1998, and references therein). It has been long believed that the hard X-ray radiation above ~1 keV emitted from hot-shocked gas can be a diagnostic for the nature of mass-loss mechanisms in classical nova outbursts together with the morphology and evolution of the nova shells. A long-sought insight into this issue has been gained with the detection of the remnant shell of nova Persei 1901 as the first resolved and detected nova shell in X-rays using the *ROSAT* High-Resolution Imager (HRI; Balman, Ögelman, & Orio 1997).

2. THE DATA AND OBSERVATIONS

The *ROSAT* HRI is sensitive in the energy range of 0.1–2.4 keV. Its in-flight, on-axis point-spread function (PSF) has a FWHM of ~6″ and is roughly independent of photon energy (David et al. 1996). GK Per and its associated shell was observed with the *ROSAT* HRI during 1996 February 10–12 for a total exposure time of 53,646.4 s. In order to study the spectrum of the shell, we also used an archival *ROSAT* Position Sensitive Proportional Counter (PSPC) observation obtained on 1992 August 17 and 30. The energy resolution of the *ROSAT* PSPC is $(\Delta E/E) \sim 0.43$ at 0.93 keV with an on-axis angular resolution of about 25″ (Pfeffermann & Briel 1986). The X-ray data presented in this Letter were analyzed using the EXSAS/MIDAS software package (Zimmermann et al. 1993).

3. THE ANALYSIS AND RESULTS

3.1. *The X-Ray Nebula*

Figure 1 is the HRI image of the nebula associated with the nova between 0.1 and 2.4 keV. The image shows emission 2 σ above the background smoothed using a Gaussian of

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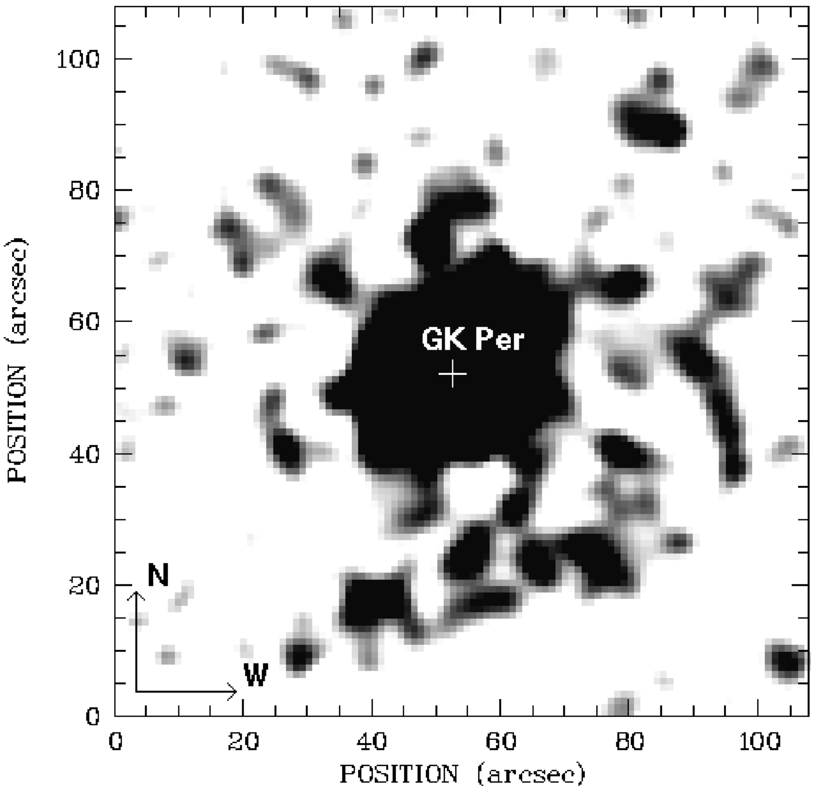

FIG. 1.—Image of the nova shell of GK Persei (1901) in the 0.1–2.4 keV energy band. The data was obtained using the *ROSAT* HRI detector. The intensity scale goes from color white as the lowest to the color black as the highest. The image shows emission 2 σ above the background and is smoothed using a Gaussian with $\sigma = 2''$. North is up, and west is toward the right.

$\sigma = 2''$. The central part of the nova shell with a radius ~16″ has not been resolved from the point source because of the wide PSF of the telescope and detector. The X-ray nebula extends to about 46″ southwest, 60″ northwest, 52″ southeast, and 43″ northeast of the point source with an elliptical shape (average radius ~0.23 pc at 470 pc source distance; McLaughlin 1960). It shows a lumpy morphology. The size of the knots/clumps vary between 4″ and 8″ in diameter constrained with the 4″ spatial resolution of the X-ray telescope. Larger features could be collections of unresolved knots/clumps. The surface brightness of the shell is 2.0×10^{-5} counts s^{-1} $arcmin^{-2}$, derived using an annulus with an inner radius ~16″ and an outer radius 50″. The count rate from the half of the nebula centered at the southwest is two-thirds the count rate from the whole shell, which is 0.01 ± 0.001 counts s^{-1}.

We aligned the X-ray image of the shell with the recent optical images obtained using the 4.2 m William Herschel Telescope (WHT) at La Palma, Canary Islands in 1993 (T. J. O'Brien 1998, private communication) and the *Hubble Space Telescope* in 1995–1997 (M. Shara 1998, private communication). Figure 2 shows the X-ray contours superposed on the [N II] image of the nova shell taken with the WHT. The southwestern quadrant of the X-ray nebula is more abundant in knots/clumps compared with the northeastern quadrant as in the optical images, and it does not show a well-developed shell. The optical knots ([N II], [O III], Hα) do not exhibit a one-to-one correspondence with the X-ray knots in general (i.e., since X-ray knots are less dense and hotter regions compared to the optical knots). Both optical and X-ray maps suggest large-scale density gradients in the vicinity of GK Persei. The bipolar nebula associated with the nova together with a wind from the secondary star, as noted earlier, could be the origin of such density gradients.

In addition, we also aligned the X-ray image with the radio contour image at 4.9 GHz obtained using the VLA in 1984 (E. R. Seaquist 1998, private communication). Enhanced X-ray emission is detected in the vicinity of the radio maxima in the southwestern quadrant of the nebula. On the other hand, there seems to be a lack of X-ray emission coincident with the edge of the shell (i.e., the radio ridge). This suggests that the X-ray nebula is smaller then the radio shell. However, more recent radio observations are necessary for a better comparison with the X-ray data. The radio data have been interpreted as a signature of a circumstellar shock propagating into the local ISM. The size of the X-ray–emitting region is larger than the width (~15″) of the forward shock zone suggested by Seaquist et al. (1989). Considering this and the fact that the radio shell is larger, we suggest that the X-ray nebula could be the reverse shock zone as well. Overall, the knots/clumps detected in the X-rays are most likely the condensations in the postshock material as a result of the Rayleigh-Taylor instabilities in the turbulent gas behind the shock.

3.2. *An Estimation on the Spectrum*

The *ROSAT* HRI does not have adequate spectral resolution. It is only suitable for hardness ratios between energy channels which could be used to estimate relative temperatures. However, a raw X-ray spectrum of the nebula can be obtained using the HRI data. Figure 3 shows the raw spectrum in which the bulk of X-ray emission is below ~1 keV (the unresolved central part of the nebula is excluded). The count rate ratio of the point

FIG. 2.—X-ray intensity contours (*ROSAT* HRI) superposed on the optical [N II] image of the nova shell of GK Persei (1901). The optical image was obtained using the 4.2 m William Herschel Telescope, La Palma, Canary Islands (Slavin et al. 1995). The resolution of the superposed image is about 0″.6 pixel^{-1}.

source and the X-ray nebula is ~5:1, respectively. This indicates that only 20% of the X-ray flux in the 0.1–2.4 keV energy range is coming from the remnant, which is consistent with the upper limit of 35% set with the *Einstein* HRI (Cordova & Mason 1984).

In order to study the spectrum of the X-ray nebula, we also used an archival *ROSAT* PSPC observation obtained in 1992. The PSPC spectrum of the nova (point source + shell; the *ROSAT* PSPC does not resolve the two) can be fitted best with a two-temperature Raymond-Smith model of thermal plasma emission (Raymond & Smith 1977), and a nonthermal model (i.e., power law) is inconsistent with the data. The PSPC results show that the low-temperature spectral component has a neutral hydrogen column density ($N_{\rm H}$) of $(1.3 \pm 0.3) \times 10^{21}$ cm^{-2}, an X-ray temperature of $(1.9 \pm 0.3) \times 10^{6}$ K (~0.16 keV), and an emission measure (EM $= \int n_e\, n_{\rm H}\, dV$) of about $(1.5 \pm 0.8) \times 10^{55}$ cm^{-3}. The higher temperature component has about the same emission measure with an $N_{\rm H} \sim (16.0 \pm 4.0) \times 10^{21}$ cm^{-2} and an X-ray temperature of $(1.1 \pm 0.5) \times 10^{7}$ K (~0.9 keV). The χ^2_ν of this fit is ~1.8, and the indicated errors correspond to the 95% confidence level. We estimate that the low-absorption–low-temperature component has the most contribution from the X-ray nebula taking into account the raw HRI spectrum (which is below ~1 keV). Therefore, the spectral parameters of the nova shell are: an $N_{\rm H} \sim 1.3 \times 10^{21}$ cm^{-2}, an X-ray temperature $\sim 2 \times 10^{6}$ K, and an emission measure $\sim 3.0 \times 10^{54}$ cm^{-3}. The unabsorbed nebular X-ray flux is $\sim 3.0 \times 10^{-12}$ ergs cm^{-2} s^{-1}, which implies a luminosity of $\sim 8.0 \times 10^{31}$ ergs s^{-1} at the 470 pc source distance. The estimated X-ray temperature is a factor of 10 cooler then the prediction of Seaquist et al. (1989). The fragmentation and clumping of the material must have caused more effective cooling behind the shock.

It is important to note that we cannot assign a particular spectrum to the nova shell since our estimation is done indirectly together with the PSPC observation. The nova shell is scheduled for a 100 ks observation with the *AXAF* satellite. This will permit us to study the spectrum of the X-ray nebula in more detail and search for a possible nonthermal component using the high sensitivity and broad energy range of the *AXAF* detectors.

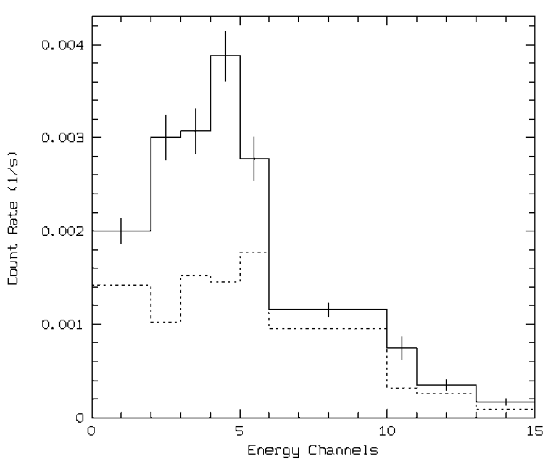

FIG. 3.—Raw spectrum of the nova shell of GK Persei (1901) obtained from the *ROSAT* HRI data. The *y*-axis is the count rate (counts s^{-1}), and the *x*-axis shows the HRI energy channels where each channel correspond to ~0.153 keV between 0.1 and 2.4 keV. The solid line is the shell + background, and the dotted line is the background raw spectrum.

4. DISCUSSION

Considering emission 2 σ above the background in the image as originating from the nebula and that the filling factor can be expressed as $f = N\Phi^3/\theta^3$, where N is the number of knots/clumps (∼60), θ is the effective angular radius of the whole shell (∼45″), and Φ is the average angular radius of a knot/clump (∼2″), one can calculate a range $0.005 \leq f \leq 0.3$ for the filling factor. If $\mathrm{EM} = n_e^2 V_{\mathrm{eff}}$, then for $0.005 \leq f \leq 0.3$ and an EM of 3.0×10^{54} cm^{-3}, the electron density in the knots/clumps is $10.0\ \mathrm{cm}^{-3} \leq n_e \leq 70.0\ \mathrm{cm}^{-3}$. The mass of the nova shell can be approximated using $M_{\mathrm{shell}} \simeq n_e m_{\mathrm{H}} V_{\mathrm{eff}}$, yielding a range between 5.0×10^{-5} and $5.0 \times 10^{-4}\ M_{\odot}$, consistent with M_{eject} and the expectation that the ejecta must have swept up several times its own mass by now.

The multiwavelength analyses of the data on the nova remnant have revealed that the shell was in a pre-Sedov phase (Seaquist et al. 1989). However, the low-energy spectrum detected in the X-rays and the low X-ray temperature of the nebula contradict the X-ray characteristics of a circumstellar shock in the pre-Sedov/Sedov phase (see review by Chevalier 1990). Therefore, a more elaborate model of shock evolution for the nova remnant as in the evolution of Type II supernova remnants might better explain the X-ray observations, in which a circumstellar shock propagates into the ambient medium and a reverse shock is formed as the fast incoming ejecta is stopped (Chevalier & Fransson 1994, and references therein). An early cooling phase can be expected at the reverse shock front depending on the steepness of the density gradient in the ejecta which, in turn, determines the reverse shock speed and the energy band of the reverse shock emission. Considering that the shell is in a pre-Sedov/Sedov phase (Seaquist et al. 1989), what is detected as the X-ray nebula may be the reverse shock zone. The existence of an evolved secondary, lumpy morphology, and larger radio shell also suggest this (see § 3.1). There is no detailed theoretical framework on the shock evolution in classical nova remnants; however, the circumstellar interaction of nova shells have been modeled for recurrent novae (RS Oph: Bode & Kahn 1985; T Pyx: Contini & Prialnik 1997). These models are not very compatible with the X-ray nebula of GK Persei, since they are for particular cases and the cooling timescales are shorter. On the other hand, they do predict a forward shock zone in which a blast wave propagates outward into a previously ejected shell and a reflected (reverse) shock wave propagates back through the new ejecta. The reverse shock zone is also expected to be clumpy because of instabilities. We would like to note that the high-density gradient in the vicinity of the nova suggests that the circumstellar medium might already be lumpy and the X-ray emission could be produced from the crushing of the cloudlets as the shock encounters them. For $n_{\mathrm{H}} \leq 100\ \ \mathrm{cm}^{-3}$, cloud crushing will be an important factor that could shift the X-ray spectrum to lower energies, below 1 keV (Draine & Woods 1991).

The X-ray observation of the shell of GK Persei is the missing link that combines the evolution of a nova shell right after outburst and long after this stage. The fact that no significant detection of old classical nova remnants has been made in the X-rays is largely constrained by the insufficient spatial resolution and effective area of the present X-ray telescopes (the best resolution has been 4″). Also, the surface brightness of classical nova remnants decreases very rapidly because of expansion. Most of the classical novae that have been detected to emit hard X-rays during the *outburst stage* share common characteristics: $M_{\mathrm{eject}} > 5 \times 10^{-5}\ M_{\odot}$, $V_{\mathrm{eject}} > 1000$ km s^{-1}, and $(\mathrm{Ne}/\mathrm{Ne}_{\odot}) > 40$ (Balman 1997). They also show complex shell structure with polar and equatorial winds and formation of knots in the ejecta as observed in the optical and ultraviolet wavelengths. GK Persei is also a neon nova (Payne-Gaposchkin 1957). A question that should be addressed is whether the conditions in the shell of GK Persei, at this time, are largely determined right after outburst or whether the role played by the circumstellar medium is significant. The latter seems to be the more prominent factor owing to the lack of X-ray and radio detections of old classical nova remnants (Bode, Seaquist, & Evans 1987a). The spatial spectroscopy of the nova remnant (GK Persei) in X-rays can be a powerful tool to investigate the nature of and the origin for the X-ray knots/clumps (outburst, ejecta vs. circumstellar). We expect that our follow-up work using the *AXAF* data will reveal the physical conditions in the nova shell and in return shed more light into the evolution of this nova remnant and others.

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