XMM-NEWTON OBSERVATIONS OF THE DWARF NOVA RU Peg IN QUIESCENCE: PROBE OF THE BOUNDARY LAYER

SOLEN BALMAN1, PATRICK GODON2,7, EDWARD M. SION2, JAN-UWE NESS3, ERIC SCHLEGEL4, PAUL E. BARRETT5, AND PAULA SZKODY6

1 Department of Physics, Middle East Technical University, Ankara, Turkey; solen@astro.physics.metu.edu.tr
2 Department of Astronomy & Astrophysics, Villanova University, Villanova, PA 19085, USA; patrick.godon@villanova.edu, edward.sion@villanova.edu
3 XMM-Newton Science Operations Centre, European Space Agency (ESA/ESAC), E-28691 Villanueva de la Canada, Madrid, Spain; junes@sciops.esa.int
4 Department of Physics & Astronomy, University of Texas at San Antonio, San Antonio, TX 78249, USA; eric.schlegel@utsa.edu
5 United States Naval Observatory, Washington, DC 20392, USA; barrett.paul@usno.navy.mil
6 Astronomy Department, University of Seattle, Seattle, WA 98195, USA; szkody@astro.washington.edu

Received 2011 April 28; accepted 2011 August 12; published 2011 October 20

ABSTRACT

We present an analysis of X-ray and UV data obtained with the XMM-Newton Observatory of the long-period dwarf nova RU Peg. RU Peg contains a massive white dwarf (WD, the primary star) accretes matter and angular momentum from a main- (or post-main-) sequence star (the secondary) filling its Roche lobe. The matter is transferred, at a continuous or sporadic accretion rate (Ṁ), by means of an accretion disk usually reaching all the way to the WD surface. Ongoing accretion at a low rate (quiescence) is interrupted every few weeks to months by intense accretion (outburst) of days to weeks (a DN accretion event). DNe are powerful X-ray sources with luminosities of 1030–1033 erg s−1. The X-ray emission is believed to originate in the boundary layer (BL) between the slowly rotating accreting WD and the fast rotating (Keplerian) inner edge of the accretion disk, where the material dissipates its remaining rotational kinetic energy before it accretes onto the surface of the WD. The typical DNe, i.e., those systems exhibiting normal DN outbursts, are the U Gem sub-type of DNe (according to the classification of Ritter & Kolb 2003) and are located above the period gap (Poreb > 3 hr).

RU Peg is a U Gem type DN with an orbital period Poreb = 8.99 hr, a secondary spectral type K2–5V, a primary (WD) mass Mwd = 1.29±0.16 M⊙, and a secondary mass M2 = 0.94 ± 0.04 M⊙ (Stover 1981; Wade 1982; Shafter 1983). The system has a magnitude range Vmax−Vmin ∼ 9.0–13.1 with outbursts lasting ∼20 days and recurring every ∼50 days. The near-Chandrasekhar WD mass has been corroborated by the sodium (8190 Å) doublet radial velocity study of Friend et al. (1990). They obtained a mass of 1.38±0.06 M⊙ for the WD and also found a range of inclination angles between 34° and 48° in agreement with the range of plausible inclinations found in the study by Stover (1981). More recently, a Hubble Fine Guidance Sensor (FGS) parallax of 3.55 ± 0.26 mas was measured by Johnson et al. (2003) yielding a distance of 282 ± 20 pc.

RU Peg was observed with IUE under several different observing programs, both in quiescence and in outburst, and was part of several survey-like studies (e.g., La Dous et al. 1985; Verbunt 1987; Szkody et al. 1991 to cite just a few).

Sion & Urban (2002) modeled four IUE spectra obtained in deep quiescence with accretion disks and phospthores. They found that a very hot WD dominated the FUV spectrum with a temperature Teff = 50–53,000 K which places RU Peg among the hottest WDs in DNe. The distance corresponding to their best fitting, high gravity (Log(g) = 8.7) photosphere models was 250 pc.

More recently, Godon et al. (2008) modeled the Far Ultraviolet Spectroscopic Explorer (FUSE) spectrum of RU Peg in quiescence and obtained a WD with a temperature of 70,000 K,

1. INTRODUCTION

1.1. The Long-Period Dwarf Nova RU Peg

Dwarf novae (DNe) are a class of weakly magnetic cataclysmic variables (CVs) which are interacting compact binaries in which a white dwarf (WD, the primary star) accretes matter and angular momentum from a main- or post-main- sequence star (the secondary) filling its Roche lobe. The matter is transferred, at a continuous or sporadic accretion rate (Ṁ), by means of an accretion disk usually reaching all the way to the WD surface. Ongoing accretion at a low rate (quiescence) is interrupted every few weeks to months by intense accretion (outburst) of days to weeks (a DN accretion event). DNe are powerful X-ray sources with luminosities of 1030–1033 erg s−1. The X-ray emission is believed to originate in the boundary layer (BL) between the slowly rotating accreting WD and the fast rotating (Keplerian) inner edge of the accretion disk, where the material dissipates its remaining rotational kinetic energy before it accretes onto the surface of the WD. The typical DNe, i.e., those systems exhibiting normal DN outbursts, are the U Gem sub-type of DNe (according to the classification of Ritter & Kolb 2003) and are located above the period gap (Poreb > 3 hr).

RU Peg is a U Gem type DN with an orbital period Poreb = 8.99 hr, a secondary spectral type K2–5V, a primary (WD) mass Mwd = 1.29±0.16 M⊙, and a secondary mass M2 = 0.94 ± 0.04 M⊙ (Stover 1981; Wade 1982; Shafter 1983). The system has a magnitude range Vmax−Vmin ∼ 9.0–13.1 with outbursts lasting ∼20 days and recurring every ∼50 days. The near-Chandrasekhar WD mass has been corroborated by the sodium (8190 Å) doublet radial velocity study of Friend et al. (1990). They obtained a mass of 1.38±0.06 M⊙ for the WD and also found a range of inclination angles between 34° and 48° in agreement with the range of plausible inclinations found in the study by Stover (1981). More recently, a Hubble Fine Guidance Sensor (FGS) parallax of 3.55 ± 0.26 mas was measured by Johnson et al. (2003) yielding a distance of 282 ± 20 pc.

RU Peg was observed with IUE under several different observing programs, both in quiescence and in outburst, and was part of several survey-like studies (e.g., La Dous et al. 1985; Verbunt 1987; Szkody et al. 1991 to cite just a few).

Sion & Urban (2002) modeled four IUE spectra obtained in deep quiescence with accretion disks and phosphores. They found that a very hot WD dominated the FUV spectrum with a temperature Teff = 50–53,000 K which places RU Peg among the hottest WDs in DNe. The distance corresponding to their best fitting, high gravity (Log(g) = 8.7) photosphere models was 250 pc.

More recently, Godon et al. (2008) modeled the Far Ultraviolet Spectroscopic Explorer (FUSE) spectrum of RU Peg in quiescence and obtained a WD with a temperature of 70,000 K,
a rotational velocity of 40 km s\(^{-1}\), assuming Log(g) = 8.8 and a distance of 282 pc. In this later study, the higher temperature obtained in the model fitting is mainly a consequence of the assumed larger distance and gravity. It is clear that RU Peg has a massive WD and therefore a deep potential well, and its surface temperature is very large (>50,000 K), possibly pointing to strong accretional and BL heating. For these reasons, we chose RU Peg as our X-ray target, as it is expected to be a copious source of X-rays and should be an ideal candidate to study its BL.

1.2. The Boundary Layer

The BL is the region between the slowly rotating accreting WD and the fast rotating (Keplerian) inner edge of the accretion disk. For accretion to occur, gravity has to overcome the centrifugal acceleration, and this happens in the BL as the material dissipates its remaining rotational kinetic energy before being accreted onto the surface of the WD. In the BL the rotational velocity is sub-Keplerian and decreases inward.

For a star rotating at 10% of the breakup velocity, Equation (2) gives 
\[ L_{BL} = (1 - \beta^2) L_{\text{disk}} = (1 - \beta^2) \frac{GM_* \dot{M}}{2R_s}, \]
where \( G \) is the gravitational constant, \( M_* \) is the mass of the accreting star, \( R_s \) is its radius, \( M \) is the mass accretion rate, and \( \beta \) is the stellar angular velocity in Keplerian units \( \beta = \Omega_*/\Omega_K(R_s) \). For most systems the WD rotational velocity is of the order of a few 100 km s\(^{-1}\) and one therefore has \( \beta \ll 1 \) and \( L_{BL} \approx L_{\text{disk}} \). For a star rotating at (e.g.) 10% of the breakup velocity Equation (1) gives \( L_{BL} = 0.99 L_{\text{disk}} \). However, the standard disk theory does not take into account the BL explicitly. Using a one-dimensional approach, Kluzniak (1987) has shown that part of the BL (kinetic) energy actually goes into the spinning of the star in the equatorial region, and the BL luminosity is more accurately given by the relation
\[ L_{BL} = (1 - \beta^2) L_{\text{disk}}. \]

For a star rotating at 10% of the breakup velocity, Equation (2) gives \( L_{BL} = 0.81 L_{\text{disk}} \), which is significantly different than Equation (1).

Because of its small radial extent, the BL is expected to emit its energy in the X-ray bands \( L_{BL} \approx L_{X-ray} \). At high accretion rate (or during DN outburst), the BL is expected to be optically thick with a temperature \( T \approx 10^5 \) K (Godon et al. 1995; Popham & Narayan 1995) and emits in the soft X-ray band. Observations of CVs in high state (e.g., Mauche et al. 1995; Baskill et al. 2005) confirm these predictions. At low mass accretion rate (or during DN quiescence), as the density is much decreased, the BL becomes optically thin and emits in the hard X-ray band with \( T \approx 10^6 \) K (Narayan & Popham 1993) (see below for observational evidence of such optically thin BLs). Hence, during quiescence the emission should arise from a very hot plasma very close to the WD surface.

Previous X-ray observations of DN systems in quiescence (e.g., van der Woerd & Heise 1987; van Teeseling & Verbunt 1996; Belloni et al. 1991), while confirming the presence of hard X-ray, deduced that, contrary to the theory, the quiescent BL luminosity was underluminous. Namely, they found \( L_{BL} = L_{X-ray} \ll L_{\text{disk}} \), which confirmed the original claim that BLs were actually missing (Ferland et al. 1992). However, these earlier results assumed the disk to be the source of the optical and ultraviolet radiation \( (L_{\text{disk}} = L_{opt} + L_{UV}) \) and used Equation (1) rather than Equation (2). More recently, X-ray Multi Mirror-Newton (XMM-Newton) observations of eight DNe in quiescence by Pandel et al. (2003, 2005) revealed that a significant part of the emitted FUV flux \( (L_{UV}) \) actually originates from the WD itself, and the evidence for underluminous BLs in quiescent DNe was refuted. For RU Peg, FUSE observations (Godon et al. 2008) indicate that the WD contributes most of the FUV light with a temperature \( T > 50,000 \) K. In addition, Godon & Sion (2005) noted that the region where the BL meets the inner edge of the Keplerian disk (Popham 1999) can also contribute some FUV flux. It is clear now that one cannot just compare the X-ray luminosity to the optical + UV luminosity to check whether the boundary luminosity is as large as the disk luminosity.

For the eight DNe caught in quiescence, Pandel et al. (2003, 2005), using the XMM-Newton data, obtained X-ray BL luminosities of the order of \( \sim 1 \times 10^{31} \) erg s\(^{-1}\) to \( \sim 6.6 \times 10^{32} \) erg s\(^{-1}\), with temperatures ranging from \( \sim 8 \) to \( 55 \) keV, and mass accretion rates deduced from X-rays in the range \( 10^{-12} \) to \( 10^{-10} \) M\(_\odot\) yr\(^{-1}\). In this work, we present XMM-Newton observations of RU Peg taken in quiescence to derive its X-ray luminosity and gain information on its BL.

2. OBSERVATIONS AND ANALYSIS

The XMM-Newton Observatory (Jansen et al. 2001) has three 1500 cm\(^2\) X-ray telescopes each with an European Photon Imaging Camera (EPIC) at the focus. Two of the telescopes have Multi-Object Spectrometer (MOS) CCDs (Turner et al. 2001) and the last one uses pn CCDs (Strüder et al. 2001) for data recording. There are two Reflection Grating Spectrometers (RGSs; den Herder et al. 2001). The Optical Monitor (OM), a photon counting instrument, is a co-aligned 30 cm optical/UV telescope, providing for the first time the possibility to observe simultaneously in the X-ray and optical/UV regime from a single platform (Mason et al. 2001).

RU Peg was observed (pointed observation) with XMM-Newton for a duration of 53.1 ks on 2008 June 9 at 07:16:50.0 UTC (obsID 0551920101). At that time the system was at a visual magnitude of \( \sim 12.5 \), about 2 months into quiescence and 2 weeks before the next outburst (from AAVSO data\(^8\)). Data were collected with the EPIC MOS and pn cameras in the prime partial window2 and prime full window imaging mode, respectively, the RGS and the OM using the fast imaging mode (\( \leq 0.5 \) s time resolution) with the UVW1 filter (240–340 nm).

We analyzed the pipeline-processed data using Science Analysis Software (SAS) version 9.0.0. Data (single- and double-pixel events, i.e., patterns 0–4 with Flag = 0 option for pn and patterns \( \leq 12 \) with Flag = 0 for MOS1,2) were extracted from a circular region of radius 60″ for pn and 45″ MOS1 and MOS2 in order to perform spectral analysis together with the background events extracted from a source free zone normalized to the source extraction area. We checked the pipeline-processed event file for any existing flaring episodes and no sporadic events in the background were detected with count rate higher than 0.08 counts s\(^{-1}\) (for MOS1,2) and 0.5 for pn detectors. Table 1 displays the background subtracted count rates for the EPIC pn, MOS1, and MOS2.

---

\(^8\) http://www.aavso.org/
Figure 1. EPIC X-ray light curve (binned at 16 s, in red) together with the OM UV light curve (binned here at 100 s for display, in black; the data were binned at 20 s for the correlation check). The count rate of the UV data has been divided by 9.1736 to fit the count rate level of the X-ray data for easier comparison. The time \( t = 0 \) corresponds to \( t = 3.29389320 \times 10^8 \) s, counted from the MJD reference day 50,814, namely 54,626.376 MJD. The time modulation of the UV data follows closely the time modulation of the X-ray data except around \( t \approx 12 \) ks, 20–22 ks, 31 ks, and 48.5 ks, where the UV has relatively more flux.

(A color version of this figure is available in the online journal.)

Table 1

| Instrument | Count Rate (s\(^{-1}\)) |
|------------|-------------------------|
| RGS2       | 0.2881 ± 0.0030         |
| RGS1       | 0.2351 ± 0.0029         |
| EPIC pn    | 10.03 ± 0.017           |
| EPIC MOS1  | 3.154 ± 0.0084          |
| EPIC MOS2  | 3.241 ± 0.0085          |

The RGS observations were carried out using the standard spectroscopy mode for readout. We reprocessed the data using the XMM-SAS routine rgsproc. We first made event files and determined times of low background from the count rate on CCD 9 (which is closest to the optical axis). The final exposure times and net count rates showed that there were no sporadic high background events in our data. Table 1 displays the background-subtracted count rates for RGS1 and RGS2. Source and background counts for the RGS were extracted using the standard spatial and energy filters for the source position, which defines the spatial extraction regions as well as the wavelength zero point.

2.1. X-Ray and UV Light Curves

The UV and EPIC pn X-ray light curves are shown together for comparison in Figure 1, where we have scaled the UV count rate to fit the X-ray count rate for a better comparison. The count rate for the UV data ranges between \( \sim 50 \) counts s\(^{-1}\) and \( \sim 100 \) counts s\(^{-1}\) with a time average of \( \sim 71.8 \) counts s\(^{-1}\). For UV-bright objects, a count rate of 1 s\(^{-1}\) in the UVW1 filter translates into a flux of \( 4.5 \times 10^{-16} \) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\) at 290 nm (see the online XMM-Newton documentation\(^9\)). This gives for RU Peg a flux of \( \approx 2.2–4.5 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\), corresponding to a luminosity of \( \approx (2.1–4.3) \times 10^{29} \) erg s\(^{-1}\) Å\(^{-1}\) (at a distance \( d = 282 \) pc). The time modulation of the UV data follows closely the time modulation of the X-ray data except around \( t \approx 12 \) ks, 20–22 ks, 31 ks, and 48.5 ks, where the UV has relatively more flux for a duration of several hundred seconds (and up to 1000 s). Since the UV is expected to be

---

\(^9\) [http://xmm.vilspa.esa.es/external/xmm_user_support/documentation/uhb/index.html](http://xmm.vilspa.esa.es/external/xmm_user_support/documentation/uhb/index.html)
emitted further out than the X-rays, these four epochs where the UV light curves do not decrease as much as the X-rays might be due to the occultation of the X-ray emitting material by the WD, while the UV emitting region is not hidden from the observer.

In order to study the correlation between the X-ray and the UV variability, we calculated the cross-correlation between the two light curves. We used time bins of 5 s averaging several power spectra with 128 bins for the analysis. The resulting correlation coefficient as a function of time lag is shown in Figures 2(a) and (b). The correlation coefficient is normalized to have a maximum value of 1. The curve shows a clear asymmetry indicating the existence of time delays. We also detect a strong peak near zero time lag suggesting a significant correlation between X-rays and the UV light curves. We call this the undelayed component (see Figures 2(a) and (b)). The positive time lag in the asymmetric profile shows that the X-ray variations are delayed relative to those in the UV. In order to calculate an average time lag that would produce the asymmetric profile, we fitted the varying cross-correlation by two Lorentzians, with time parameter fixed at 0.0 lag and the other set as free. The resulting fit yields a lag of 116 ± 17 s. This is the delayed component.

2.2. EPIC Spectrum

We performed spectral analysis of the EPIC data using the SAS task ESPECGET and derived the spectra of the source and the background together with the appropriate response matrices and ancillary files. How the photons were extracted is described in Section 2. The EPIC pn, EPIC MOS1, and EPIC MOS2 spectra were simultaneously fitted to derive the spectral parameters. The spectral analysis was performed using XSPEC version 12.6.0q (Arnaud 1996). A constant factor was included in the spectral fitting to allow for a normalization uncertainty between the EPIC pn and EPIC MOS instruments. We grouped the pn and MOS spectral energy channels so that there is a minimum of 80 (MOS1,2) to 150 (pn) counts in a bin to improve the statistical quality of the spectra. The fits were conducted in the 0.2–10.0 keV range. The simultaneously fitted spectra from the three EPIC instruments are shown in Figure 3. We modeled the X-ray spectrum of RU Peg in a similar fashion as Pandel et al. (2005) and fitted the data with the (TBabs × CEVMKL) model within XSPEC. TBabs is the Tuebingen–Boulder ISM absorption model (Wilms et al. 2000) and CEVMKL is a multi-temperature plasma emission model built from the mekal code (Mewe et al. 1985). Emission measures follow a power law in temperature (i.e., emission measure from temperature $T$ is proportional to $(T/T_{\text{max}})^{-\alpha}$). The residuals in Figure 3 show systematic fluctuation around the 6.7–6.9 keV iron line complex mainly from the EPIC pn data and some small low-energy fluctuations exist in the MOS2 data as well. This is due to the charge transfer inefficiency (CTI) problem in the pn (and possibly MOS2) instrument. These generally occur around lines due to small calibration errors and mostly effect only the line shapes leaving systematic residuals and increasing the reduced $\chi^2$ of the fits. Our EPIC MOS1 data do not exhibit any CTI effects and the reduced $\chi^2$ for the fit to these data alone is 1.15 (dof 290). The reduced $\chi^2$ for the simultaneously fitted spectra is higher than the value for the MOS1 fit, but the spectral parameters for all three instruments are almost the same within the errors. Table 2 contains the spectral parameters from fits (using three detectors simultaneously) with the (TBabs × CEVMKL) model. Errors are given at the 90% confidence level. We find a...
X-ray flux is $4.1 \pm 0$ neon which we calculate to be subsolar. The unabsorbed mostly solar abundances of elements aside from oxygen and silicon appears to be slightly enhanced in abundance and silicon appears to be slightly enhanced compared to solar abundance. The resolution of the RGS spectrum has a lower count rate and a lower upper energy boundary (i.e., 2.5 keV) compared with the EPIC data (i.e., 12 keV). We find that most of the RGS spectral parameters are consistent with the EPIC results. Oxygen and neon are subsolar in abundance and silicon appears to be slightly enhanced compared to solar abundance. The resolution of the RGS spectra is sufficient to measure the rotational velocity of the BL via Doppler broadening of emission lines. We calculated the broadening using the O viii emission line at 19 Å which is the strongest line in the spectrum. We used a Gaussian model to calculate the $\sigma$ of the line ($\sigma = 2.4 \times \text{FWHM}$) along with a power law/bremmstrahlung for the continuum. Since proper response is not utilized by the fluxed spectrum, in order to perform a similar spectral fit/analysis using the same (TBabs $\times$ CEVMKL) model within XSPEC, we used the count rate spectra produced for RGS1 and RGS2 simultaneously with the appropriate response files for each detector. This is a very efficient approach to find the spectral parameters in comparison with the EPIC results. The fitted RGS1 and RGS2 spectra are shown in Figure 5. Table 4 contains the spectral parameters from the fit with the (TBabs $\times$ CEVMKL) model within XSPEC. Errors are at the 90% confidence level and the fit is performed between 0.2 and 2.5 keV.

The maximum temperature from the fits with the RGS data yields 24 keV with a large error range of 17–41 keV since the spectrum has a lower count rate and a lower upper energy boundary (i.e., 2.5 keV) compared with the EPIC data (i.e., 12 keV). We find that most of the RGS spectral parameters are consistent with the EPIC results. Oxygen and neon are subsolar in abundance and silicon appears to be slightly enhanced compared to solar abundance. The resolution of the RGS spectra is sufficient to measure the rotational velocity of the BL via Doppler broadening of emission lines. We calculated the broadening using the O viii emission line at 19 Å which is the strongest line in the spectrum. We used a Gaussian model to calculate the $\sigma$ of the line ($\sigma = 2.4 \times \text{FWHM}$) along with a power law/bremmstrahlung for the continuum. We find that

### Table 2
Spectral Parameters of Fit to the Combined EPIC Spectrum of RU Peg in the Energy Range 0.2–10 keV

| Parameter       | Value             |
|-----------------|-------------------|
| $N_H$ (10$^{22}$ atoms cm$^{-2}$) | 0.044$^{+0.003}_{-0.001}$ |
| $\alpha$        | 1.05$^{+0.03}_{-0.03}$ |
| $T_{\text{max}}$ (keV) | 31.7$^{+2.0}_{-2.0}$ |
| O               | 0.3$^{+0.06}_{-0.06}$ |
| Ne              | 0.55$^{+0.16}_{-0.16}$ |
| Mg              | 1.3$^{+0.2}_{-0.2}$ |
| Si              | 0.8$^{+0.14}_{-0.14}$ |
| S               | 0.9$^{+0.3}_{-0.2}$ |
| Ca              | 1.8$^{+0.8}_{-0.8}$ |
| Fe              | 0.8$^{+0.04}_{-0.04}$ |
| $K_{\text{CEVMKL}}$ | 0.047$^{+0.001}_{-0.001}$ |
| Gaussian LineE (keV) | 6.4 (fixed) |
| $\sigma_G$ (keV) | 0.19$^{+0.025}_{-0.025}$ |
| Flux (10$^{-11}$ erg cm$^{-2}$ s$^{-1}$) | 4.1$^{+0.2}_{-0.2}$ |
| $\chi^2$ (dof) | 1.5 (1741) |

### Notes.
$N_H$ is the absorbing column, $\alpha$ is the index of the power-law emissivity function ($dE M = (T/T_{\text{max}})^{\alpha}$ $dT/T_{\text{max}}$), $T_{\text{max}}$ is the maximum temperature for the CEVMKL model. Element names stand for the abundance relative to solar abundances, Gaussian lineE is the line center for the emission line, $\sigma_G$ is the line width; $K_{\text{CEVMKL}}$ and $K_G$ are the normalizations for CEVMKL and Gaussian models, respectively. The unabsorbed X-ray flux is given in the range 0.2–10.0 keV. All error ranges are given at the 90% confidence level ($\Delta \chi^2 = 2.71$ for a single parameter).

### Table 3
Line Identifications of the XMM-Newton RGS Spectrum of RU Peg

| Ion   | Wavelength (Å) |
|-------|----------------|
| Mg xi | 7.20           |
| Ne x  | 12.15          |
| Fe xvii | 15.03        |
| O viii | 16.05          |
| Fe xvii | 16.80         |
| Fe xvii | 17.07          |
| O viii | 19.00           |
| O vii (i) | 21.80        |
| O vii (f) | 22.11        |
| N vii | 24.77           |

### Figure 4.
Fluxed RGS Spectrum of RU Peg with line identifications.

The RGS analysis tool rgsproc was used to obtain RGS1 and RGS2 spectra and to produce a fluxed spectrum (i.e., using rgsfluxer). The resultant fluxed spectrum of the combined RGS1 and RGS2 detectors is shown in Figure 4 with line identifications. The detected lines and corresponding wavelengths are listed in Table 3. Fluxed spectra are obtained just by dividing the count spectrum by the RGS effective area. It neglects the redistribution of monochromatic response into the dispersion channels.
FWHM = 0.044 Å and the corresponding velocity in the line of sight is 695 km s\(^{-1}\) (\(\Delta \lambda / \lambda = v/c\)). We also checked the resolution of RGS at around 19 Å and found 0.04–0.05 Å and we caution that our measurement is on the limit of the RGS spectral resolution.

3. DISCUSSION

The maximum X-ray shock temperature we obtain is 29–33 keV, based on the EPIC MOS1,2 and pn data, as they have higher count rates and broader energy ranges than the RGS data. RU Peg has a harder X-ray spectrum than in most DNe, but softer than U Gem in quiescence, which also contains a massive WD (Sion et al. 1998; Long & Gilliland 1999). This result is consistent with and confirms the large mass of the WD in RU Peg.

The X-ray luminosity of RU Peg is 4.1 × 10\(^{32}\) erg s\(^{-1}\) (0.2–10.0 keV), and assuming we see only half of the BL (if it is close to the star), we have \(L_{\text{BL}} = 8.2 \times 10^{32}\) erg s\(^{-1}\). This is in the range of the other quiescent DNe observed with XMM-Newton by Pandel et al. (2005). However, in order to fully compared RU Peg with these other systems, we also need to consider the UV luminosity. For the UV we use the spectral luminosity at 290 nm, as derived by Pandel et al. (2005) for quiescent DNe observed with XMM-Newton. We have added RU Peg on the graph. The solid and dotted lines show \(L_{\text{BL}} = L_{\text{disk}} (= L_{\text{UVW1}})\) assuming UV luminosity predicted by a simple accretion disk model with an inner radius \(r_{\text{in}} = 5000 \text{ km}\) and 10,000 km, respectively. For systems higher above the line, such as RU Peg, the UV excess is due to the contribution from the WD. The UV luminosity of a WD with an 8000 km radius at various temperature is shown on the left. RU Peg corresponds here to a ∼53,350 K WD with a radius of 8000 km (which we have also added to the original graph), which translates to ∼75,000 K for a 4000 km WD, more in line with the large mass of the WD in RU Peg. WX Hyi was caught in outburst explaining its UV excess.
The modeling of the O VI emission line at 19 Å implies a projected rotational broadening \( v_{\text{rot}} \sin i = 695 \text{ km s}^{-1} \), i.e., the line is emitted from material rotating at \( \sim 936 - 1245 \text{ km s}^{-1} \) (since \( i \sim 34^\circ - 48^\circ \)) or about 1/6 of the Keplerian speed. This velocity is still much larger than the rotation speed of the WD inferred from the FUSE spectrum (40 km s\(^{-1}\); Godon et al. 2008). This implies that the X-ray emission comes directly from the decelerating BL material. It is possible that the X-ray emission originates in the equatorial region of the WD as shown by Piro & Bildsten (2004), who found that poloidal motion may be negligible at low mass accretion rates characteristic of DNe in quiescence. In such a case most of the dissipated energy is radiated back into the disk, which may justify the use of a one-dimensional treatment (such as Narayan & Popham 1993; Popham 1999).

The X-ray luminosity we computed corresponds to a BL luminosity (Equation (2)) for a mass accretion rate of \( 2.0 \times 10^{-11} M_\odot \text{ yr}^{-1} \) assuming a 1.29 \( M_\odot \) WD mass, and it increases to \( 3.0 \times 10^{-11} M_\odot \text{ yr}^{-1} \) for a 1.2 \( M_\odot \) WD mass. This is entirely consistent with a quiescent accretion rate.

We checked the correlation between the variability of the X-ray data and the UV data and found two components: one delayed and the other undelayed. The X-ray and UV emission originates in the equatorial region of the WD as shown by Piro & Bildsten (2004), who found that poloidal motion may be negligible at low mass accretion rates characteristic of DNe in quiescence. In such a case most of the dissipated energy is radiated back into the disk, which may justify the use of a one-dimensional treatment (such as Narayan & Popham 1993; Popham 1999).

The X-ray data and the UV data and found two components: one delayed and the other undelayed. The X-ray and UV emission originates in the equatorial region of the WD as shown by Piro & Bildsten (2004), who found that poloidal motion may be negligible at low mass accretion rates characteristic of DNe in quiescence. In such a case most of the dissipated energy is radiated back into the disk, which may justify the use of a one-dimensional treatment (such as Narayan & Popham 1993; Popham 1999).

The X-ray data and the UV data and found two components: one delayed and the other undelayed. The X-ray and UV emission originates in the equatorial region of the WD as shown by Piro & Bildsten (2004), who found that poloidal motion may be negligible at low mass accretion rates characteristic of DNe in quiescence. In such a case most of the dissipated energy is radiated back into the disk, which may justify the use of a one-dimensional treatment (such as Narayan & Popham 1993; Popham 1999).

The X-ray data and the UV data and found two components: one delayed and the other undelayed. The X-ray and UV emission originates in the equatorial region of the WD as shown by Piro & Bildsten (2004), who found that poloidal motion may be negligible at low mass accretion rates characteristic of DNe in quiescence. In such a case most of the dissipated energy is radiated back into the disk, which may justify the use of a one-dimensional treatment (such as Narayan & Popham 1993; Popham 1999).

P.G. wishes to thank Bill Blair for his kind hospitality at the Johns Hopkins University where part of this work was carried out. Except for the symbol and temperature mark of RU Peg, Figure 6 was taken from Pandel et al. (2005), who kindly agreed that we reproduce Figure 4 from their original work. This work is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA member states and by NASA. Support for this work was provided by NASA through grant numbers NNX08AX43G (XMM-Newton AO7) to Villanova University.

REFERENCES

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17

Baskill, D. S., Wheatley, P. J., & Osborne, J. P. 2005, MNRAS, 357, 626

Belloni, T., Verbunt, F., Beuermann, K., et al. 1991, A&A, 246, L44

den Herder, J. W., Brinkman, A. C., Kahn, S. M., et al. 2001, A&A, 365, L7

Feild, G. J., Pepper, G., Langer, S. H., et al. 1982, ApJ, 262, L53

Friend, M. T., Martin, J. S., Smith, R. C., & Jones, D. H. P. 1990, MNRAS, 246, 654

Godon, P. 1995, MNRAS, 277, 157

Godon, P., Regev, O., & Shaviv, G. 1995, MNRAS, 275, 1093

Godon, P., & Sion, E. M. 2005, MNRAS, 361, 809

Godon, P., Sion, E. M., Barrett, P. E., et al. 2008, ApJ, 679, 1447

Inogamov, N. A., & Sunyaev, R. A. 1999, Astron. Lett., 25, 5

Jansen, F., Lumb, D., Aliieri, B., et al. 2001, A&A, 365, L1

Johnson, J. J., Harrison, T. E., Howell, S. B., et al. 2003, BAAS, 202, 0702

Kluzniak, W. 1987, Phd thesis, Standford Univ.

La Dous, C., Verbunt, F., Pringle, J. E., et al. 1985, MNRAS, 212, 231L

Long, K. S., & Gilliland, R. L. 1999, ApJ, 511, 916

Mason, K. O., Breeveld, A., Mach, R. et al. 2001, A&A, 365, L36

Mauche, C. W., Raymond, J. C., & Mattei, J. A. 1995, ApJ, 446, 842

Mewe, R., Gronenschild, E. H. M., & van den Oord, G. H. J. 1985, A&AS, 62, 197

Narayan, R., & Popham, R. 1993, Nature, 362, 820

Pandel, D., Córdova, F. A., & Howell, S. B. 2003, MNRAS, 346, 1231

Pandel, D., Córdova, F. A., Mason, K. O., & Friedhorsky, W. C. 2005, ApJ, 626, 396

Piro, A. L., & Bildsten, L. 2004, ApJ, 610, 977

Popham, R. 1999, MNRAS, 308, 979

Popham, R., & Narayan, R. 1995, ApJ, 442, 337

Popham, R., & Sunyaev, R. 2001, ApJ, 547, 355

Pringle, J. E. 1981, A&A & A, 10, 137

Revnivtsev, M., Potter, S., Kniasez, A., et al. 2011, MNRAS, 411, 1317

Ritter, H., & Kolb, U. 2003, A&A, 404, 301

Shafter, A. 1983, PhD thesis, Univ. California, Los Angeles

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337

Shakura, N. I., & Sunyaev, R. A. 1988, Adv. Space Res., 8, 135

Sion, E. M., Cheng, F. H., Szkody, P., et al. 1998, ApJ, 496, 449

Sion, E. M., & Urban, J. 2002, ApJ, 572, 456

Stover, R. 1981, ApJ, 249, 673

Strüder, L., Briel, U., Dennerl, K., et al. 2001, A&A, 365, L18

Szkody, P., Stabine, C., Mattei, J. A., & Waagen, E. O. 1991, ApJS, 76, 359

Turner, M. J. L., Abbey, A., Arnaud, M., et al. 2001, A&A, 365, L27

van der Woerd, H., & Heise, J. 1987, MNRAS, 225, 141

van Teeseling, A., & Verbunt, F. 1996, A&A, 292, 519

Verbunt, F. 1987, A&AS, 71, 339

Wade, R. 1982, AJ, 87, 1558

Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914