THE SSS PHASE OF RS OPHIUCHI OBSERVED WITH CHANDRA AND XMM-NEWTON. I. DATA AND PRELIMINARY MODELING

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ABSTRACT

The phase of supersoft source (SSS) emission of the sixth recorded outburst of the recurrent nova RS Oph was observed on days 39.7 and 66.9 after outburst with Chandra and on day 54.0 with XMM-Newton. A ~35 s period on day 54.0 originates from the SSS emission and not from the shock. We discuss the bound-free absorption by neutral elements in the line of sight, resonance absorption lines plus self-absorbed emission-line components, collisionally excited emission lines from the shock, He-like intersetyn lines, and spectral changes during an episode of high-amplitude variability. We find a decrease of the oxygen K-shell absorption edge that can be explained by photoionization of oxygen. The absorption component has average velocities of ~1286 ± 267 km s⁻¹ on day 39.7 and of ~771 ± 65 km s⁻¹ on day 66.9. The wavelengths of the emission-line components are at rest wavelengths, as confirmed by measurements of non-self-absorbed He-like intersetyn lines. We found collisionally excited emission lines from the radiatively cooling shock at wavelengths shorter than 15 Å that are systematically blueshifted by ~526 ± 114 km s⁻¹ on day 39.7 and are fading. We found anomalous He-like f/i ratios, which indicates either high densities or significant UV radiation near the plasma where the emission lines are formed. During the phase of strong variability the spectral hardness light curve overlies the total light curve when shifted by 1000 s. This can be explained by photoionization of neutral oxygen in the line of sight if the densities are of order 10¹⁰–10¹¹ cm⁻³.

Subject headings: stars: individual (RS Ophiuchi) — novae, cataclysmic variables — X-rays: stars

1. INTRODUCTION

RS Oph is a symbiotic recurrent nova (RN) that had recorded outbursts in 1898, 1933, 1958, 1967, 1985, and 2006 (February 12.83 = day 0; Hirosawa et al. 2006). In previous outbursts RS Oph was well studied in the optical, and in 1985 it was followed extensively in ultraviolet (Shore et al. 1996 and references therein), radio (Padin et al. 1985; Hjellming et al. 1986), and X-rays (six pointings by EXOSAT from day 55 to day 251 of the outburst; Mason et al. 1987; O’Brien et al. 1992).

RS Oph is a member of a small class of cataclysmic variables (CVs), in which a white dwarf (WD) orbits a red giant secondary (M2 III). The orbital period is 455.7 ± 0.3 days, and assuming a WD near the Chandrasekhar limit and a low inclination (i < 40°), the red giant mass is of order 0.5 M☉ (Dobrzycka & Kenyon 1994). The distance to RS Oph has been well determined by a variety of methods at 1.6 ± 0.3 kpc (Bode 1987). The interstellar absorbing column, N_H = (2.4 ± 0.6) × 10²¹ cm⁻², was determined from H i 21 cm measurements (Hjellming et al. 1986) and is consistent with the visual extinction (E(B − V)) = 0.73 ± 0.1 determined from the International Ultrasiolet Explorer (IUE) observations in 1985 (Snijders 1987).

Just as in classical novae (CNe), accretion of material from the secondary causes an explosion on the WD surface. However, in RNe the rate of mass accretion and the WD mass are sufficiently large for outbursts to repeat on human timescales. (The other members of this class are T CrB, V745 Sco, and V3890 Sgr.) A RN evolves analogously to a CN, the major difference between the two types of outburst arises from the presence of the red giant in the binary system, which completely changes the environment around the WD. The evolution of the X-rays in RS Oph can be characterized by four phases:

1. The explosion ejects material into its surroundings and produces a strong shock moving into the wind and outer atmosphere of the red giant and backward into the ejecta (e.g., Bode et al. 2006; O’Brien et al. 2006; Sokoloski et al. 2006). The strength of the shock depends on the kinetic energy of the ejecta and the density of the medium into which the ejecta run.

2. While nuclear burning continues on the WD, the bolometric luminosity is approximately constant (Gallagher & Code 1974). Depending on the opacity due to electron scattering within the expanding shell, the peak of the observed spectrum gradually shifts from soft X-rays to soft X-rays (Gallagher & Code 1974). In CNe this happens after a few weeks to months (e.g., V4743 Sgr; Ness et al. 2003b), and the spectrum resembles that of the class of supersoft X-ray sources (SSSs; Kahabka & van den Heuvel 1997). This phase is therefore called the SSS phase.

12 The companion of the WD is generally a main-sequence star instead of a giant.
3. After the end of nuclear burning on the WD, the SSS emission decreases and RS Oph enters a phase in which a recombining plasma, exhibiting emission lines from radiatively excited states, appears.

4. The final stage is that of the ejected material radiatively cooling. Collisionsal bound-bound excitations are balanced by radiative de-excitation, giving rise to emission lines (also called the coronal approximation). In this way kinetic energy is effectively converted into radiation.

The first few weeks of the evolution of the X-ray-emitting blast wave in RS Oph were studied by Sokoloski et al. (2006) using the Rossi X-Ray Timing Explorer (RXT) and Bode et al. (2006) using Swift. The shock wave was also extensively studied at radio wavelengths by Very Long Baseline Interferometry (VLBI) and MERLIN imaging observations (O’Brien et al. 2006). From these observations and those obtained with the Hubble Space Telescope (Bode et al. 2007) and with ground-based infrared interferometers (VLTI+AMBER; Chesneau et al. 2007), asymmetries and multiple emission components have clearly been established that show that there is jet-like ejection in addition to shell-like ejection of material. In the 2006 outburst Chandra obtained one, and XMM-Newton obtained two observations of this phase (Ness et al. 2006a; J. J. Drake et al. 2006, in preparation; Gonzalez-Riestra et al. 2006; J.-U. Ness 2007, in preparation).

The SSS phase commenced about 30 days into the outburst (Osborne et al. 2006b). Early in the evolution, the energy output of a nova explosion happens primarily at optical and UV wavelengths, because the high-energy radiation produced by nuclear burning on the surface of the WD will be scattered within the surrounding shell, leaving the atmosphere as lower energy radiation. When the surrounding shell becomes thinner as a consequence of the expansion, the optical brightness decreases while the X-ray brightness increases and originates from deeper within the outflow. X-ray observations during this phase allow studies of the plasma regions at the radial distance from the WD within the outflow. The SSS spectrum is sufficiently narrow as to be resolved in its diagnostic features, and the spectral changes during brightness variations detected during the first observation in §3.5. We discuss various possible interpretations in §4 and summarize our conclusions in §5.

## 2. OBSERVATIONS

During the SSS phase that started after day 26 (2006 March 10), three grating observations were carried out by Chandra (Weisskopf et al. 2002) and XMM-Newton (Jansen et al. 2001). We summarize the dates of each observation, the respective days after the outburst, instrumental setup, observation identification numbers (ObsIDs), and the net exposure times in Table 1. The first and last observations were taken by Chandra with net exposure times of 10.0 and 6.5 ks, respectively. As a consequence of the brightness of the source, telemetry saturation occurred, which reduced the effective exposure times to 8.0 and 5.0 ks, respectively. Provisions were taken to ensure that these reduced spectra were correctly calibrated. We used the LETGS/HRC combination (Low Energy Transmission Grating/High Resolution Camera; Brinkman et al. 2000; Murray et al. 2000), which is an imaging dispersion spectrometer. Higher dispersion orders are not filtered out, but in our case contamination of the first-order spectrum by higher order photons is negligible because the SSS spectrum is sufficiently narrow as to prevent an overlap of the dispersion orders.

The second grating observation during the SSS phase was taken with XMM-Newton on day 54 after outburst (2006 April 7). XMM-Newton carries five X-ray instruments, three low-resolution CCD detectors, and two gratings (Reflection Grating Spectrometers RGS1 and RGS2: den Herder et al. 2001). Due to the unexpected brightness of the target, the allocated telemetry rates were not sufficient to handle the large event rate. All instruments were affected by telemetry saturation. This implies that the effective exposure times were shorter than the on-target times. For the RGS2, the net exposure time was 18.6 ks, but it was only 9.8 ks in the RGS1 (total on-target time was 18.9 ks). Since the telemetry losses do not depend on the energy of the photons, they have no effect on the extracted spectrum, except for the shorter net exposure time. However, the light curves were strongly affected, since telemetry losses cannot be recovered. The X-rays dispersed into the spectrum by reflecting off the RGS are recorded with a strip of CCD detectors, and the wavelength range is 5–38 Å. Unfortunately, two chips within these CCD arrays failed early
in the mission, and those portions of the dispersed spectrum that
should be recorded by these chips are lost. The wavelengths
affected by the chip failure range from 10.5–13.8 Å in the RGS1
and 20–24 Å in the RGS2. Since the peak emission of our SSS
spectrum ranges between 15 Å and ~30 Å (see § 2.2 and Fig. 3),
only the RGS1 gives us sufficient spectral information, and we
concentrate primarily on the RGS1 for spectroscopy. We use the
RGS2 for light-curve analyses. Since the source spectrum has its
peak in the middle of the RGS2 chip gap (Fig. 3), the RGS2 col-
lects fewer photons and is less affected by telemetry losses. This
may be the only example where the chip gap is actually of use,
providing us with the only useful light curve of this observation.

We present our extraction of the light curves in § 2.1 and that
of the spectra in § 2.2. We used standard tools provided by the
mission-specific software packages SAS (Science Analysis Soft-
ware, ver. 7.0) and CIAO (Chandra Interactive Analysis of Ob-
servations, version 3.3.0.1).

2.1. Extraction and Analysis of Light Curves

Chandra.—For the extraction of Chandra light curves we
used the CIAO tool lightcurve, which extracts all photons
within previously defined source and background extraction re-
gions on the detector. As source extraction regions we chose two
polygons around the streaks of dispersed photons including both
dispersion directions and we used only the middle chip (i.e., \( \lambda < 
50 \) Å). The background was extracted from adjacent regions and
subtracted.

XMM-Newton.—For the extraction of XMM-Newton RGS2
light curve we used the SAS tool evselect, which extracts all
dispersed photons within standard source- and background ex-
traction regions. We extracted the RGS2 light curve in four
different bin sizes in time, all chosen to be multiples of the readout
time (4.5947 s) in order to search for periodicity.

In Figure 1 we show the Chandra light curves in 50 s time
bins in units of ks after the start of each observation. In the ob-
servation of day 39.7, the count rate increases rapidly by a factor
of 2 within only 1000 s, remaining at a high count rate for about
3000 s, then dips down (a little bit lower than the start count rate),
only to rise again with an even steeper slope toward the end of the
observation. In Figure 2 we show the RGS2 light curve extract
for day 54.0, which is much flatter than that on day 39.7, but is
not as flat as on day 66.9. For the latter light curve we investi-
gated the possibility of rapid variability; however, a simple model
assuming a constant emission level reproduces the measured light
curve with a reduced \( \chi^2 = 0.94 \), and thus models including any
kind of variability cannot improve the fit by more than 68.3%.

We computed a power spectrum for all light curves, and for
days 39.7 and 66.9 we find no significant periodic variations. In
order to search for periods shorter than 50 s, we also extracted the
Chandra light curves in smaller time bins, but did not detect any
periods longer than 2 s. In the bottom panel of Figure 2 we show
the result from the period search of the RGS2 light curve. In this
observation we find a 34.8 s period that is consistent with the
\( \approx 35 s \) period reported by Osborne et al. (2006b). We also found a

![Fig. 1.—Light curves of the Chandra LETG observations, days 39.6 and 66.9, in time bins of 50 s. The light curves have been extracted from the dispersed photons covering a wavelength range \( \approx 6–50 \) Å. For the first observation we extracted separate spectra from the time intervals marked with different shadings (see Fig. 9).](image1)

![Fig. 2.—RGS2 light curve (day 54.0) in 45.947 s time bins (10 times readout time; top) and periodogram (bottom). A \( \approx 35 s \) periodicity is found in the RGS2 light curve that confirms observations of a similar period with Swift reported by Osborne et al. (2006c).](image2)
Absorption component:

emission levels between days 39.7, 54.0, and 66.7 by computing out during a phase of higher emission. We compared the relative pared to day 39.7. This explains the higher

changes are consistent with the changes of the corresponding

Within the uncertainties of the flux variations on day 39.7, the

variable light curve taken with

fourth variability was not always present, disappearing entirely

after day 63 (2006 April 17).

period of ~5.3 s, which is the beat period of the instrument readout time (4.5947 s) and the 34.8 s period. We extracted the light curves from each chip and found this period only on those chips that recorded the SSS spectrum.

Our reanalysis of the Swift light curves obtained on days ≈39.7, 54.0, and 66.9 indicated that the ~35 s periodicity is only present on day 54.0. Osborne et al. (2006c) reported that this periodic variability was not always present, disappearing entirely after day 63 (2006 April 17).

We compared the emission levels in the grinding spectra with those of Swift at the same times. The first observation was taken during the phase of highly variable soft X-ray flux reported in Osborne et al. (2006a, 2006b). This phase lasted from days 29 to 46 (Osborne et al. 2006c) and is thus coincident with the highly variable light curve taken with Chandra on day 39.7. Since Swift light curves are never continuous over more than at most 2 ks due to its orbit, it is the Chandra light curve that demonstrates that the source was actually variable on timescales shorter than 0.1 days.

Close inspection of the Swift monitoring light curve (J. Osborne et al. 2007, in preparation) revealed that the first Chandra observation (day 39.7) was taken at a time when the Swift count rate was close to one of the minima during the variability phase, while the second Chandra observation (day 66.9) was taken during the decline shortly after the peak emission level had been reached. This explains the higher Chandra count rate on day 66.9 compared to day 39.7. The XMM-Newton observation was carried out during a phase of higher emission. We compared the relative emission levels between days 39.7, 54.0, and 66.7 by computing the photon fluxes by integration of the grinding spectra (see § 2.2). Within the uncertainties of the flux variations on day 39.7, the changes are consistent with the changes of the corresponding Swift count rates.

2.2. Extraction of Spectra

Grating spectra are extracted on an equidistant wavelength grid (in units of Å), and we use wavelength units throughout this paper. We extracted the spectra with the Chandra CIAO tool tgrsextract for the LETGS observations and the XMM-Newton SAS tool rgsproc for the RGS observation. These routines place standardized extraction regions over the dispersed photons on the detector and are optimized to maximize the ratio of collected source counts to the included background. The mirror point spread function is translated into an instrumental line profile that is ap-

proximately Lorentzian for the RGS and more Gaussian-like for Chandra LETG (both FWHM ~ 0.055 Å at all wavelengths, corresponding to 500–1100 km s⁻¹ from 30 to 10 Å, respectively). Velocities below these values that contribute to line broadening are difficult to determine. However, velocities from line shifts can be determined accurately (see Table 2 in § 3.2). Using standard tools to calculate the effective areas (in cm²) and then dividing a count rate by the effective area at the corresponding wavelength results in a photon flux that is sufficiently independent of the instrument (RGS vs. LETGS). Thus, the photon flux spectra from the RGS1 and the LETGS can be compared (see Fig. 3).

Chandra.—The dispersed photons are recorded in two streaks in opposite directions from the zeroth order, delivering two independent spectra. We co-added these two spectra for best signal- to-noise ratio. In addition, independent analyses of the spectra can be carried out for consistency checks. In Figure 3 we present the two Chandra observations (light and dark shadings) along with the XMM-Newton observation (solid line).

XMM-Newton: RGS data were processed with the SAS task rgsproc in SAS version 7.0 up to the creation of the merged, filtered event file. This file was manipulated to correct for pileup. Given the high flux of the source, spectra were extracted from the

| Ion: | O vii | O viii | N vi | N vii | Fe xvii |
|------|-------|-------|------|-------|--------|
| \( \lambda \) (Å) | 21.60 | 18.97 | 28.78 | 24.78 | 15.01 |
| \( \nu \) | 0.68 | 0.83 | 0.66 | 0.83 | 2.52 |

| PARAMETER | Day 39.7 | Day 66.9 |
|-----------|----------|----------|
| Absorption component: | | |
| \( \nu \) | -1143 \( ^{+99} \) \( ^{-99} \) | -685 \( ^{+101} \) \( ^{-101} \) |
| Flux \( ^{+17} \) \( ^{-17} \) | -1264 \( ^{+477} \) \( ^{-477} \) | -772 \( ^{+91} \) \( ^{-91} \) |
| Emission component: | | |
| \( \nu \) | 0.79 \( ^{+0.83} \) \( ^{-0.83} \) | 1.04 \( ^{+0.66} \) \( ^{-0.66} \) |
| Flux \( ^{+0.83} \) \( ^{-0.83} \) | 3.38 \( ^{+0.104} \) \( ^{-0.104} \) | 4.53 \( ^{+0.39} \) \( ^{-0.39} \) |

a Oscillator strength.
b Velocity from line shift (km s⁻¹).
c Optical depth at line center.
d Column density (10¹⁵ cm⁻²). Uncertainties in \( \nu \) were calculated at fixed wavelengths and with fixed emission-line parameters and are underestimated.
e Emission line flux (10⁻¹⁰ erg cm⁻² s⁻¹).
full field of view instead of using standard extraction regions, and no background subtraction was applied. The separation of spectral orders was accomplished by using the energy resolution of the CCDs. Pileup occurs when two or more events arrive at the same (or neighboring) pixel during the same readout frame. These photons are registered as a single event with an energy that is the sum of the energies of the individual events. In our case, pileup results in events with CCD-measured energies $nE$ (where $n = 1, 2, 3, 4$), while the photons are dispersed according to their individual wavelengths. Due to this pileup, counts occur in the energy-dispersion plane in regions normally associated with higher orders. There is no ambiguity between pileup and higher order dispersion due to the narrow spectral range of the supersoft continuum spectrum. We were thus able to reconstruct the true spectrum before pileup by adding those events in the energy-dispersion plane back into the first-order spectrum that resulted from pileup in the first-order spectrum. The rates of the new first-order spectra are about 30% higher than before this correction.

For a qualitative comparison of the spectra from the different missions we converted all three count rate spectra into photon flux spectra. We do not correct for the redistribution matrix, so the line profiles will still depend on the individual instrumental point-spread function (PSF). However, the shape of the continuum is not affected by the instrumental PSF, as it is very small compared to the width of the continuum.

In Figure 3 we compare the photon flux spectra of the three grating observations. The integrated fluxes relative to each other are consistent with the relative count rates Swift measured at the respective times. All spectra show continuum emission over the same wavelength range with similar shapes. At 22.83 Å there is a strong absorption edge in all spectra that is clearly noninstrumental and originates from O i (K-shell ionization). Also, an expected narrow 1s–2p absorption line at 23.5 Å (Paerels et al. 2001) from atomic oxygen can be identified in all three spectra. At ~29 Å there are emission-line features in all spectra that we attribute to N v i (see § 3.4). Strong absorption lines can be identified in all three spectra (see § 3.2).

3. SPECTRAL ANALYSIS

3.1. Continuum Emission and Broadband Absorption

In order to understand the cause of the brightness changes we computed a series of blackbody models and found reasonable agreement with the measured spectra for temperature ranges (630–830)×10$^3$ K on day 39.7, (650–710)×10$^3$ K on day 54.0, and (590–720)×10$^3$ K on day 66.9. The bolometric luminosities, log ($L_{bol}$), of these models are between 37.3 and 38.5 for day 39.7, 38.5 and 38.9 for day 54.0, and 38.2 and 39.3 for day 66.9. We used a standard model for interstellar plus circumstellar absorption. The value of hydrogen column density $N_H$ was greater than the interstellar value ($N_H = 2.4 \times 10^{21}$ cm$^{-2}$) for all models (more below). However, the values of reduced $\chi^2$ (see § 3.4) are greater than 20 for all models, and no secure conclusions can be drawn from these numbers. In particular, we do not claim from these models that super-Eddington luminosities occurred. With these limitations we are not able to explain the brightness changes in terms of temperature or luminosity.

As a first approach to characterize the shape of the continuum, we computed hardness ratios HR = (H – S)/(H + S) from the three spectra with H and S denoting the fluxes extracted from within the wavelength ranges 15–23 and 23–30 Å, respectively. We found values of ~0.06, +0.12, and +0.03 with 4%, 1%, and 8% uncertainties for days 39.7, 54.04, and 66.9, respectively. Changes in hardness generally imply a change in temperature, but changes in broadband absorption (bound-free transitions) by elements in the line of sight can also lead to changes in spectral hardness. We estimated the optical depth of the O i absorption edge at 22.83 Å from the intensities of the continuum, $\tau = \ln \left(\text{cont}_{22.8}/\text{cont}_{>22.8}\right)$, and found $\tau = 0.9, 0.5, and 0.7$ for days 39.7, 54.0, and 66.9, respectively. This implies that the larger hardness ratio on day 54 was caused by reduced O i within the material in the line of sight.

In order to investigate this effect closer, we use the blackbody models from above as continua and apply an absorption model that accounts for variations of the neutral oxygen abundance. We optimized the blackbody parameters temperature and bolometric luminosity simultaneously with the parameters of the absorption model.

The continuum spectrum produced by the WD atmosphere has to pass through the circumstellar and the interstellar material in the line of sight. The former may be partially ionized while the latter consists of neutral elements of solar composition. The bound-free absorption imposed by this material leads to element-specific absorption edges that are detectable with the LETGS (e.g., Paerels et al. 2001). The depth of these edges depends on the elemental composition and absorption cross sections, e.g., for K-shell absorption by neutral oxygen. Absorption edges from higher ionization stages also depend on the fractional number density of the ion. We parameterize bound-free absorption in the line of sight by the column density of neutral hydrogen, $N_H$. While the column density of the interstellar material is assumed constant in all observations, it may vary with time in the circumstellar material. We, therefore, split the absorption into two terms, one term with fixed $N_H$ and one with variable $N_H$, both with solar composition (Grevesse & Sauval 1998). We computed the total transmission coefficients as implemented in the software package PINToFALe (Kashyap & Drake 2000) from the single parameter $N_H$. Using this model we account only for absorption from the neutral component of the absorbing column while absorption by ionized elements is included only for helium.

In Figure 4 we present the three spectra from the gratings (in photon flux units) in comparison with our best-fit continuum plus absorption models. First, we optimized the blackbody parameters and the value of $N_H$ that represents the neutral component of the circumstellar material with the abundances fixed at solar (Grevesse & Sauval 1998). In the top right corner of each panel we give the value of $\chi^2_{red}$. These models are identical to the ones described above, and are formally unacceptable. The blackbody continuum seems to represent the rough observed spectral shape. However, the high resolution of the gratings clearly exposes the shortcomings of blackbody models with many spectral features not being reproduced.

Next, we varied the abundance of the oxygen content within the circumstellar component, while the interstellar oxygen abundance remained fixed at solar. We fit the oxygen abundance simultaneously with the blackbody parameters and $N_H$ and include the best-fit models with gray lines in Figure 4. Although, these models are also formally unacceptable, an improvement in $\chi^2_{red}$ is apparent. The resulting best-fit abundances suggest that after day 54 all neutral oxygen in the circumstellar material has disappeared. We note that for day 66.9 the optical depth around the edge was higher than on day 54.0, suggesting that the neutral oxygen abundance has increased again. The model for day 66.9 does not show this increase, but the peak is not well modeled. The blackbody temperatures of these models are (540–760)×10$^3$ K on day 39.7, (520–580)×10$^3$ K on day 54.0, and (440–590)×10$^3$ K on day 66.9. The bolometric luminosities, log ($L_{bol}$), of these models are between 37.6 and 39.2 for day 39.7, 39.3 and 40.0 for day 54.0, and 38.9 and 40.5 for day 66.9. Comparison
with the parameters of the models with the oxygen abundance fixed at solar shows that the introduction of the oxygen abundance as a free parameter introduces considerable additional uncertainty in the blackbody parameters.

The simplest explanation for the reduction of neutral oxygen is photoionization of the circumstellar material by the radiation field. We tested this hypothesis and computed models with reductions of other elements that would also have to be ionized (nitrogen and carbon with their K-shell absorption edges at 30.25 and 43.63 Å, respectively). We were not able to find a model that reproduced the measured spectrum better than the one with only oxygen reduced. Next, we carefully inspected the grating spectra for evidence of any absorption edges at the ionization energies of $\text{O}^{\, \text{vii}}$ (16.77 Å), $\text{O}^{\, \text{viii}}$ (14.23 Å), $\text{N}^{\, \text{vi}}$ (22.46 Å), and $\text{N}^{\, \text{vii}}$ (18.59 Å).

In all three spectra, there is no evidence for these absorption edges. Since the continuum level at these wavelengths is sufficiently high, and the instruments are sensitive enough to detect these edges, we conclude that no absorption edges from H-like and He-like ions are present. This indicates that the material that produces the absorption lines from high-ionization stages (see next section) contributes little bound-free absorption and resides deeper within the outflow.

Paerels et al. (2001) pointed out that the detailed structure of the spectrum around the O edge is extremely complex, consisting of absorption lines and edges for various ions and molecular species. For example, we studied the $\text{O}^{\, \text{i}} 1s-2p$ absorption line at 23.62 Å. On days 39.7 and 66.9 we found this line at the same wavelength of 23.51 Å and with the same optical depth at line center of $\tau_p = 1.4$. This similarity suggests that this line was formed in a nonchanging medium (interstellar medium). The shift of this line is similar to shifts 30–50 mÅ found by Juett et al. (2004) for various features from singly and doubly ionized oxygen in HETG spectra of seven X-ray binaries, which are consistent with discrepancies between theoretical calculations and laboratory measurements. It is thus likely that the 23.51 Å line is the $\text{O}^{\, \text{i}} 1s-2p$ line at the rest wavelength. We also found evidence for the $1s-2p$ absorption lines of $\text{O}^{\, \text{ii}}$ to $\text{O}^{\, \text{v}}$, expected at 23.3, 23.11, 22.78, and 22.33 Å, respectively (see also Table 3), which indicates that we are not only dealing with atomic oxygen.

Juett et al. (2004) have developed detailed models for the wavelength range around the oxygen K-shell absorption edge. These models allow determinations of the ratios of ionization stages and oxygen column densities and lead to a more accurate bound-free absorption model needed for further analyses. Similar analyses have been carried out by Page et al. (2003); however, in no other source is the oxygen edge as deep as in RS Oph.

Alternatively to ionization, Paerels et al. (2001) propose that grain formation could reduce the O edge. In the event of dust formation in the outer regions of RS Oph, oxygen could have been locked up in grains.
3.2. Modeling of Resonance Absorption and Emission Lines

The Chandra and XMM-Newton grating spectra are the only spectra that allow us to identify and study absorption and emission lines. In Figure 5 we show small portions of the Chandra count spectra of days 39.7 and 66.9, focused on the wavelength ranges of four prominent lines, projected on a velocity scale (assuming the rest wavelengths $\lambda_0$ given in the legends). We modeled these spectral regions with three components, a continuum (normalized blackbody), an absorption-line component, and an emission-line component. We include the emission-line component in order to determine if we are seeing P Cygni profiles (Ness et al. 2006b). We restrict the model to the narrow spectral region around each line in which the emission-line component can dramatically change those values. Integration over the entire absorption-line profile allows us to estimate absorbing column densities, $x_{ne}$ for each line. We use the oscillator strengths given in Table 2. The emission-line fluxes represent the intrinsic line fluxes, including self-absorption, corrected for interstellar plus circumstellar absorption. Integration over the entire absorption-line profile allows us to estimate absorbing column densities, $x_{ne}$ for each line. We use the oscillator strengths given in Table 2. The emission-line fluxes and column densities depend strongly on the choice of $N_{HI}$(ISM) + $N_{HI}$(CS), especially at long wavelengths.

We calculated uncertainty ranges for the model parameters $\lambda_{a,e}$, $\sigma_{a,e}$, $A$, and $E$ separately by calculating a grid of $\chi^2_{red}$ over a given range of the respective parameters. For each grid point all other parameters were optimized, respecting the boundary condition of the individual parameter of interest to be fixed at the given grid value. The 1 $\sigma$ uncertainty ranges were then obtained by interpolating the grid until $\chi^2_{red}$ had increased by unity. If the curve was found to be too flat so that $\chi^2_{red}$ never reached values higher than one above the minimum for a sensible range of values, then lower or upper limits were calculated. Next, the uncertainties of $\lambda_{a,e}$ and $\sigma_{a,e}$ were translated into the respective uncertainties in velocity, and those of $A$ and $E$ into the uncertainties of $\tau_e$ and emission-line fluxes, respectively. For $\tau_e$ we only considered variations of $A$, but we allowed all other parameters to be optimized before a value of $\chi^2_{red}$ was calculated for a given $\tau_e$.

The uncertainties of the column densities were obtained by calculating a grid of $\chi^2_{red}$ from a range of pairs of $A$ and $\sigma_e$ that represent a grid of values of $x_{ne}$ and probing the range of $\chi^2_{red} + 1$. The uncertainties of $\tau_e$ and $x_{ne}$ do not explore the full uncertainty range as variations of the central wavelength of the emission-line component can dramatically change those values. In particular if saturation is reached, we loose all constraints. This is a shortcoming of our parameterized model that cannot deal with saturation self-consistently. For now, the given uncertainty ranges represent the minimal uncertainties within which no changes can be considered significant. We have also not included uncertainties from the amount of interstellar and circumstellar absorption.

### Table 3

| $\lambda'$ | $\tau_e$ | $\lambda_0$ | ID$^a$ | $\lambda'$ | $\tau_e$ | $\lambda_0$ | ID$^a$ |
|-----------|---------|-------------|-------|-----------|---------|-------------|-------|
| 14.93...... | 0.86    | 15.01       | Fe xvi | 23.51...... | 1.41    | 23.62       | O i   |
| 15.77...... | 0.41    | 15.87       | Fe xvii| 23.66...... | 0.35    | 23.78       | N vi  |
| 15.94...... | 0.92    | 16.00       | O viii | 24.50...... | 0.24    | 24.51       | S xiv |
| 16.71...... | 0.43    | 16.78       | Fe xvi | 24.69...... | 0.93    | 24.78       | N vii |
| 16.99...... | 0.48    | 17.05       | Fe xvi | 25.61...... | 0.57    | 25.68       | Ar xiv|
| 17.69...... | 1.00    | 18.97       | O vii ?| 25.76...... | 0.25    | 25.84       | Ar xiv|
| 18.88...... | 0.75    | 19.83       | N vii  | 25.91...... | 0.21    | 26.00       | Ar xiv|
| 19.84...... | 0.43    | 20.68       | S xiv ?| 26.07...... | 0.51    | 26.12       | N vii |
| 20.63...... | 0.44    | 20.91       | N vii  | 26.82...... | 1.06    | 26.99       | C vii |
| 21.52...... | 0.83    | 21.60       | O vii  | 27.30...... | 0.42    | 27.47       | Ar xiv|
| 22.25...... | 0.56    | 22.33       | O v    | 27.52...... | 0.79    | 27.64       | Ar xiv|
| 22.64...... | 1.18    | 22.78       | O iv   | 27.83...... | 0.49    | 27.90       | Si xii |
| 22.93...... | 1.06    | 22.97       | Ca xvi ?| 28.00...... | 0.55    | 28.11       | Fe xvii|
| 23.16...... | 0.31    | 23.11       | O iii  | 28.65...... | 0.70    | 28.78       | N vii |
| Or         | 23.29    | N vii       |        | 29.80...... | 0.66    | 29.91       | Fe xvii|
| 23.36...... | 0.25    | 23.30       | O iv   | 30.35...... | 1.59    | 30.47       | Ca xii|
| 23.69...... |         |             |        | 31.29...... | 0.94    | 31.32       | Fe xvii|

$^a$ In Å units.

$^b$ Question marks indicate uncertain identifications.
In Figure 5 we compare the count spectra with the models $M(\lambda)$ after iteration of $C, E, A, \lambda_{\text{cm}}, \sigma_v, \lambda_{\text{cm}}$, and $\sigma_v$ (eq. [1]). The relevant spectral ranges are well fitted, and the values of $\chi^2_{\text{red}}$ are below 1.2 for day 39.7 and below 3.0 for day 66.9. In Table 2 we list the line-shift velocities, optical depths at line center, and emission-line fluxes, derived from the model parameters with their uncertainty ranges for the absorption- and emission-line components.

The optical depths in the line centers are unity within the uncertainties for all lines in both observations, which is consistent with our expectation that we are observing regions in the outflow where $\tau = 1$. In Figure 5 we add dashed lines to denote the respective models for which $\tau = 1$ was enforced during the fit. For N vii (day 66.9) we were not able to constrain any of the parameters because the absorption trough is quite flat. An optical depth of $\tau = 1$ leads only to an acceptable fit if the absorption line is assumed to be very narrow and leads to an increase in $\chi^2$ in only one spectral bin (see Fig. 5, top right panel).

The column densities could not be sufficiently constrained to assess whether they varied significantly from day 39.7 to day 66.9. Only N vii, and possibly N vi, exhibited a decrease of column density within the given errors. However, we caution that uncertainties from the emission-line component and the continuum, as well the amount of interstellar-circumstellar absorption, are not included in these error estimates.

Within each observation the absorption-line velocities are consistent with $-1286 \pm 267 \text{ km s}^{-1}$ for day 39.7 and $-771 \pm 65 \text{ km s}^{-1}$ for day 66.9 (weighted averages). This marks a clear reduction in the measured expansion velocity. The line widths, although dominated by the instrumental line profile, have systematically but not significantly decreased. We tested models where we fixed all line widths at the instrumental resolution ($\sigma_{\text{gauss}} = 0.03 \text{ Å}$ at all wavelengths) and found acceptable fits except for N vii.

The potential of this approach over global approaches is that we can concentrate on single lines that are least affected by blending or other uncertainties that are more difficult to disentangle in complex atmosphere models. We found optical depths at line centers of unity. The second reliable result at this stage is the decrease of the characteristic velocity consistently measured for five different absorption lines. Although the velocities derived from these absorption lines are very similar to those expected at these epochs from the simple shock model as applied to the Swift X-ray data (Bode et al. 2006), similar effects in these lines observed in X-rays in classical novae are commonly ascribed to observing material deeper into the envelope in which there is a velocity gradient (Hubble flow). Further, the origin of the emission-line components has to be determined before further steps can be taken. This requires a reduction of the uncertainties, which we plan to achieve by applying sensible boundary conditions.
For the observation taken on day 39.7, we first assumed only absorption lines, but an additional emission-line component was necessary in order to arrive at acceptable fits. Their nominal (line-shift) velocities range from \( \sim +300 \) to \(+600 \text{ km s}^{-1}\), but the uncertainty ranges are large and include the possibility that the emission lines could be at their rest wavelengths.

We scanned the Chandra spectrum of day 39.7 for all absorption lines that appear not to be blended and summarize the wavelengths and central optical depths \( \tau_e \) below the continuum in Table 3. We attempted identifications and found lines from N, O, Fe, S, Si, Ca, and Ar using the collisional database APED.\(^{13}\) The identifications are based on the assumption that a strong collisional excitation probability implies a strong radiative excitation probability. We searched for candidates at wavelengths that imply blue shifts of \( \sim 0.1 \) \(\AA\), as this wavelength shift is found for the well-identified lines used for Figure 5.

### 3.3. Emission Lines from the Shock

Shortward of 14 \(\AA\), we found emission lines at wavelengths where Chandra and XMM-Newton measured shock-induced emission lines before the SSS spectrum appeared (Ness et al. 2006a; Gonzalez-Riestra et al. 2006; J.-U. Ness 2007, in preparation). In Figure 6 we show the count rate spectra of this spectral range for the Chandra observations taken on days 39.7 and 66.9. In contrast to the SSS spectra on these days, the latter spectrum exhibits fainter emission lines than during the day 39.7 observation. These lines must be collisionally excited, due to the absence of any ionizing radiation of sufficient energies, and we interpret them as residual emission from the shock.

We measured wavelengths and emission-line fluxes using our line fitting tool Cora (Ness & Wichmann 2002). The wavelengths can be converted to velocities that characterize the dynamics of the plasma that produces these lines. For day 39.7 we found a small systematic line shift from all lines that translate to a weighted average plus variance of \(-526 \pm 114 \text{ km s}^{-1}\). For the other two observations, the lines were not strong enough to estimate reliable uncertainties of the line positions.

In Table 4 we list the emission-line fluxes for the strongest lines. We have not corrected the measured fluxes for the effects of

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**Table 4**

| Ion      | \( \lambda_e \) (\(\AA\)) | Transmission Coefficient | Flux\(^d\) Day 39.6 | Flux\(^d\) Day 54.0 | Flux\(^d\) Day 66.9 | Ratio Day 39.6/Day 54.0 | Ratio Day 39.6/Day 66.9 |
|----------|---------------------------|--------------------------|---------------------|---------------------|---------------------|------------------------|------------------------|
| **Lines from Shock ("Hard Lines")** |
| Si xiv    | 6.18                      | 0.841                    | 0.897               | 112.1 \( \pm 10.6\) | 47.2 \( \pm 12.8\) | 22.1 \( \pm 6.3\)    | 0.42                   |
| Si xiii   | 6.65                      | 0.809                    | 0.876               | 336.4 \( \pm 55.5\) | 158.3 \( \pm 68.2\) | 50.9 \( \pm 33.1\)   | 0.47                   |
| Mg xii    | 8.42                      | 0.693                    | 0.793               | 196.8 \( \pm 12.3\) | 106.7 \( \pm 7.9\)  | 40.5 \( \pm 7.2\)    | 0.54                   |
| Mg x        | 9.20                      | 0.626                    | 0.744               | 386.3 \( \pm 38.1\) | 240.2 \( \pm 26.5\) | 133.3 \( \pm 27.7\)  | 0.62                   |
| Ne x       | 12.13                     | 0.390                    | 0.556               | 285.5 \( \pm 11.8\) | 105.7 \( \pm 9.3\)  | 95.2 \( \pm 8.3\)    | 0.62                   |
| Fe xvii    | 12.26                     | 0.380                    | 0.547               | 70.2 \( \pm 11.5\)  | 17.4 \( \pm 8.1\)   | 26.5 \( \pm 8.6\)    | 0.43                   |
| Ne ix      | 13.44                     | 0.290                    | 0.463               | 138.1 \( \pm 13.8\) | 42.0 \( \pm 5.5\)   | 34.1 \( \pm 11.4\)   | 0.30                   |
| Ne ix\(^e\) | 13.55                     | 0.282                    | 0.455               | 66.7 \( \pm 8.0\)   | 28.8 \( \pm 4.1\)   | 38.1 \( \pm 8.1\)    | 0.43                   |
| Ne ix\(^+\) | 13.69                     | 0.273                    | 0.445               | 104.4 \( \pm 9.9\)  | 36.4 \( \pm 3.8\)   | 52.5 \( \pm 8.4\)    | 0.35                   |
| Fe xviii   | 14.20                     | 0.239                    | 0.410               | 48.7 \( \pm 6.6\)   | ...                 | 20.7 \( \pm 9.1\)    | 0.42                   |

| Lines on Top of the SSS Spectrum ("Soft Lines") |
|-----------------------------------------------|
| Fe xvii        | 15.01                     | 0.225                    | 0.403               | 170 \( \pm 70\)     | ...                 | ...                   |
| O viii         | 18.97                     | 0.087                    | 0.226               | 848 \( \pm 140\)    | ...                 | ...                   |
| O vii          | 21.60                     | 0.031                    | 0.121               | 361 \( \pm 140\)    | ...                 | ...                   |
| O vii\(^e\)    | 21.80                     | 0.028                    | 0.115               | 381.8 \( \pm 24.6\) | ...                 | ...                   |
| O vii\(^+\)    | 22.10                     | 0.025                    | 0.106               | 418.2 \( \pm 24.6\) | ...                 | ...                   |
| N vii          | 24.78                     | 0.051                    | 0.181               | 400 \( \pm 80\)     | ...                 | 321 \( \pm 130\)     | ...                   |
| N vii\(^e\)    | 28.78                     | 0.010                    | 0.072               | 325 \( \pm 180\)    | ...                 | 247 \( \pm 250\)     | ...                   |
| N vii\(^+\)    | 29.10                     | 0.009                    | 0.066               | 282.1 \( \pm 19.1\) | ...                 | 443.9 \( \pm 31.9\)  | ...                   |
| N vii\(^+\)    | 29.54                     | 0.007                    | 0.059               | 788.5 \( \pm 27.3\) | ...                 | 397.7 \( \pm 32.6\)  | ...                   |

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\(^a\) Rest wavelengths.
\(^b\) Assuming \( N_H = 4.7 \times 10^{21} \text{ cm}^{-2}\).
\(^c\) Assuming \( 2.4 \times 10^{21} \text{ cm}^{-2}\).
\(^d\) At \( 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}\), not corrected for interstellar absorption.
\(^e\) Intersystem line

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interstellar and/or circumstellar absorption. As shown in § 3.1, our models of interstellar and circumstellar absorption are not accurate enough to derive reliable corrections. In the first four columns we list the line identifications, wavelengths, and transmission coefficients that would have to be applied under the assumptions of \(N_{\text{H}}(\text{ISM}) + N_{\text{H}}(\text{CS}) = 4.7 \times 10^{21} \text{ cm}^{-2}\) and \(N_{\text{H}}(\text{CS}) = 0\) (i.e., only interstellar absorption with \(N_{\text{H}}(\text{ISM}) = 2.4 \times 10^{21} \text{ cm}^{-2}\)) assuming solar abundances. As soon as a more accurate absorption model is available, the fluxes listed in Table 4 can be converted to unabsorbed fluxes at the source. However, if the lines originate from the shock, they may only be affected by interstellar absorption and not by circumstellar material. In the top part of Table 4 we list the line fluxes originating from the shock and in the bottom part we include the emission-line fluxes measured as part of the models described in § 3.2 for days 39.7, 54.0, and 66.9. We label these lines “hard lines” and “soft lines,” respectively. For the soft lines we reversed the correction for interstellar absorption that has been applied with the terms \(T_{\text{SM}}(\lambda)\) in equation (1) for comparison with the unabsorbed hard lines. We also include the line fluxes for He-like interstellar lines measured in § 3.4. In the last three columns we list the changes in the line fluxes between days 54.0 and 39.9, 66.9 and 54.0, and 66.9 and 39.7, respectively.

The fluxes are all of the same order of magnitude, which implies that they originate from the same plasma. In that case the soft lines considered as part of the absorption lines in § 3.2 are actually coming from the shock. This would also explain why these lines disappeared by day 66.9, which earlier had been interpreted as disappearance of P Cygni profiles (Ness et al. 2006b). However, correcting for interstellar plus circumstellar absorption will result in considerable enhancements of the fluxes of the soft lines because of their longer wavelengths, but that depends critically on the value of \(N_{\text{H}}(\text{ISM}) + N_{\text{H}}(\text{CS})\) and the applied absorption model. The resulting higher fluxes in the soft lines can be explained by photoexcitation in addition to collisional excitations. If the lines originate from the shock, only interstellar absorption has to be accounted for, leading to line fluxes that suggest a mixture of collisional excitations and photoexcitations. Otherwise, circumstellar absorption has to be added, and stronger line fluxes would have to be assumed that could be explained by a smaller distance between the radiation source and the plasma emitting the soft lines.

3.4. He-like Triplets

The most prominent transitions in the range 5–45 Å are H-like and He-like lines of elements with nuclear charge \(Z = 6\) (carbon) to \(Z = 14\) (silicon). The \(n = 2 \rightarrow 1\) transitions of He-like ions consist of three strong lines, a resonance line \((1s^2p^1P_1)\) an intercombination line \((1s^2p^1P_1)\) and a forbidden line \((f; 1s^22S_1^0)\), all decaying into the ground state \((1s^21S_0^0); \text{see, e.g., Ness et al.} 2003a\). These lines are important for two reasons. First, the measured wavelengths of the intercombination and forbidden lines can constrain the exact location of the emission-line components in the models described in § 3.2 because they are not absorbed. Second, the flux ratio \(f/i\) of the He-like triplets are important density diagnostics (e.g., Gabriel & Jordan 1969; Ness et al. 2004). In low-density environments with the presence of strong UV fields, the \(f/i\) ratios can also be used to measure the distance between the X-ray plasma and the UV source (applied, e.g., by Waldron & Cassinelli 2001 to the winds of O stars immersed in the UV radiation field from the stellar surface).

We used our line fitting tool Cora (Ness & Wichmann 2002) to determine the line positions and line fluxes of the He-like lines of O \(\upalpha\), \(\lambda_0 = (21.6, 21.8, 22.1) \AA\), and N \(\upalpha\) \(\lambda_0 = (28.7, 29.1, 29.54) \AA\), using Gaussian line profiles. We varied the line positions and found that the \(i\) and \(f\) lines are not significantly shifted from their rest wavelengths (upper limit \(\sim 600 \text{ km s}^{-1}\)). More refined models in § 3.2 can therefore be calculated with the boundary condition that the emission-line components are not shifted.

Next, we measured the line fluxes with variable line strengths and fixed wavelengths and line widths on top of a constant continuum. For O \(\upi\) we used a constant value of 9000 counts \(\text{s}^{-1}\), and for N \(\upalpha\), where the continuum is not as flat as for O \(\upi\), we used a linear continuum with a slope of \(-40\) counts \(\text{s}^{-1}\). In Figure 7 we show the spectra and our models for day 39.7.

We considered the possibility that the lines shortward of the forbidden lines (\(\sim 22\) and \(\sim 29.4 \AA\)) are blueshifted counterparts of the forbidden lines (Fig. 7, bottom panel). In that case the intercombination lines should also have blueshifted companions at the same velocity. For O \(\upi\) a model with an additional component, shifted by \(-1763.5 \text{ km s}^{-1}\), results in a good representation of the data (Fig. 7, top panel). For N \(\upalpha\) the forbidden line clearly shows a second component at a different velocity, but there is no evidence for a blueshifted component of the intercombination line at this velocity. No transitions from other ions are known for these wavelengths that would be strong enough, but these lines could be satellite lines that appear in a photoionized recombining plasma. For our further analysis we only use the fluxes measured at the rest wavelengths.

We include the measured fluxes for the \(i\) and \(f\) lines in Table 4. In a collisional plasma the sum of the fluxes in the \(i\) and \(f\) lines is expected to be of the same order as that in the resonance line \((r)\), while in a plasma where photoexcitation takes place, the ratio \(G = (f + i)/r\) should be less than 1. If this ratio is greater than 1, this indicates a purely recombining plasma or a photoionized plasma with high column densities suppressing resonant diffusion (Coupé et al. 2004; Godet et al. 2004). From the numbers in Table 4 we compute \(G = 2.2 \pm 1.2\) for O \(\upalpha\) and \(G = 3.3 \pm 2.0\) for N \(\upalpha\), both greater than 1, but with large uncertainties.

At low densities the ratio of \(R = f/i\) is expected to be 3.9 for O \(\upalpha\) and 4.9 for N \(\upalpha\) (low-density limit \(R_0\)), while in a high-density plasma, this ratio is reduced by collisional excitations from the upper level of the \(f\) line into the upper level of the \(i\) line, followed by radiative de-excitations from there into the ground. We measured \(f/i\) ratios of \(1.1 \pm 0.1\) and \(2.8 \pm 0.2\), which correspond to densities of \(n_e = 11\) and \(n_e = 10.8\) for O \(\upalpha\) and N \(\upalpha\), respectively. We used the summarized parameterized form given by, e.g., equation (2) in Ness et al. (2004) that has been derived by Gabriel & Jordan (1969) with the critical densities \(\log (N_c) = 10.5\) and \(\log (N_c) = 9.7\) for O \(\upalpha\) and N \(\upalpha\), respectively. As a first approach, we neglected the radiation term \(\phi\phi\). For comparison, Evans et al. (2007) measured densities of order \(10^5\)–\(10^{10} \text{ cm}^{-3}\) from various infrared lines between days 64 and 84, and our values are rather high compared to that. However, the IR and the X-ray emission may originate from different places in the flow, especially if the X-ray lines originate from the shock (see previous section).
range around 1630 Å is not covered. We, therefore, inspected the archive of the *IUE*, which contains a number of observations of RS Oph taken after the outburst on 1985 January 28 (e.g., Shore et al. 1996). We extracted an observation taken 1985 February 26, 23:47:00 UT (~30 days after outburst; ObsID SWP25327) and estimated flux levels for the continuum of 1/C24; 1012 ergs cm−2 s−1 at 1630 Å and 1900 Å. Emission lines near these wavelengths from He ii (1640 Å), Si iii (1892 Å), and C iii (1908 Å; Shore et al. 1996) can increase the relevant flux to no more than 1/C24; 1012 ergs cm−2 s−1. The former flux level leads to a distance between the UV source and the immersed plasma of 4 × 1011 cm (6 Ro) for O vii and 3 × 1012 cm (40 Ro) for N vii, while the latter flux leads to 9 × 1011 cm (13 Ro) and 1013 cm (180 Ro) for O vii and N vii, respectively. These numbers are quite uncertain because we assume that the UV emission level was similar during the 1985 and 2006 outbursts. However, we can conclude that if the plasma emitting these lines is further away from the UV radiation source, than 200 Ro, then the density must be higher than 1010 cm−3. This distance is small compared to the extent of the expanding shell on day 39.7. With an expansion velocity of 1100 km s−1 the shell has reached a radius of 3.8 × 1014 cm (5400 Ro).

### 3.5. Spectral Variability from High- to Low-Flux Phases

We now focus on spectral changes on shorter timescales. During the observation taken on day 39.7, variations in brightness were detected which were not seen in the other two observations. In Figure 8 we show the evolution of the observed flux integrated over the wavelength range 15–30 Å (top panel) in comparison to the hardness ratio HR (bottom panel) with the same definitions as used in § 2.2 (repeated in the legend). The rescaled light curve, marked with the gray curve in the bottom panel of Figure 8 indicates that the hardness ratio has the same shape but is retarded by 1000 s.

In order to study the spectral changes in more detail, we extracted spectra from the two different time intervals marked in
dark and light shadings in Figure 1, representing high-flux and low-flux emission. In Figure 9 we compare these spectra with the dark shading being the high-flux spectrum and the light shading the low-flux spectrum. In the bottom two panels we show the cumulative distribution of counts and the ratio spectrum, respectively.

The cumulative distribution traces the spectral shape regardless of the different intensities and can be used for a Kolmogorov-Smirnov two-sample test. At \( \frac{C_24}{27} \) \( \frac{8}{8} \) we find the largest difference of 0.03, which has to be compared to the maximally allowed difference of 0.007 if the two spectra were to be considered identical within 95% probability. The spectra are therefore different in their shapes in addition to the obvious difference of intensity. Inspection of the cumulative curve reveals that the high-flux spectrum is slightly softer.

The ratio spectrum shows up to a factor of 2 higher emission in the high-flux spectrum. The absorption lines of O \( \text{viii} \) at 19\( \frac{8}{8} \) and N \( \text{vii} \) at 25\( \frac{8}{8} \) as well as the O \( \text{i} \) absorption edge at 22.83\( \frac{8}{8} \) are deeper relative to the continuum in the high-flux spectrum. This indicates that the brightness changes involve more than changes in the brightness of the continuum. In contrast, shortward of 15\( \frac{8}{8} \), as well as near 29.5\( \frac{8}{8} \) (the wavelength of the N \( \text{vi} \) forbidden line), the two spectra are identical.

In Figure 10 we compare the high-flux and low-flux spectra around the absorption lines in velocity space. While the high-flux phase provides additional continuum emission, the emission level in the troughs of the absorption lines is unchanged. There is no detectable difference in blueshift of the absorption troughs.

We repeated our model from \( x3 \) for these two spectra. While the optical depths at line center were around unity for both spectra, the line column densities were significantly lower in the low-flux observation. For example, for O \( \text{viii} \) we found a column density of \( 6^{+39}_{-151} \) in the high-flux spectrum but only \( 2^{+93}_{-192} \) in the low-flux spectrum. The line shift velocities were the same in the models to both spectra.

4. DISCUSSION

In \( x3 \) we have presented a number of issues that can be addressed with the three grating spectra of RS Oph. The shape of the spectrum cannot be approximated by a blackbody model. The dominant feature, the O \( \text{i} \) absorption edge, changes with time. The quantitative analysis of these changes is complicated by various overlapping absorption processes. For example, the ionization edges and 1s–2p transitions from oxygen in low-ionization stages introduce significant structure to the observed spectrum. These low-ionization stages can occur in both the circumstellar and the interstellar material in the line of sight. We thus need a more refined model accounting for more processes than only K-shell ionization of neutral elements in order to understand the effects that the interstellar plus circumstellar material have on the observed spectra.
These uncertainties affect the interpretation of the origin and production mechanism of the soft emission lines listed in the bottom part of Table 4. While the hard lines at short wavelengths can only be collisionally excited and originate from the shock, the soft lines can in addition be photoexcited because of the presence of the bright SSS spectrum. The contribution from photoexcitations depends on the distance between the hot WD atmosphere that provides the radiation and the plasma that emits the soft lines. If they originate from the shock, this distance will be greater than if they are part of the hot WD atmosphere. In the latter case the soft lines should be much stronger than in the former case. However, the amount of assumed extinction will be enhanced by circumstellar material in addition to the interstellar medium, leading to lower line fluxes measured at Earth. In order to solve the ambiguity from these competing processes, an improved absorption model for interstellar and circumstellar absorption is required to derive accurate unabsorbed lines fluxes for each case. The hard lines can be used to constrain the mean emission measure distribution for a collisional plasma as developed by Ness et al. (2005) for the classical nova V382 Vel. This will be part of an upcoming paper (J. U. Ness et al. 2007, in preparation). If the soft lines originate from the shock, they will show up with an excess in the emission measure distribution, reflecting the contributions from photoexcitations. The amount of excess depends on the distance between the plasma and the hot WD atmosphere, which has to be of the same order as that between the atmosphere and the shocked plasma. We note that the disappearance of the soft emission lines between days 39.7 and 66.9 is consistent with the fading of the lines produced in the shock. The only soft lines measurable on day 66.9 were also weaker than on day 39.7, even though the SSS spectrum was brighter. We thus favor a scenario in which the soft lines originate from the shock and are partially photoexcited, while being absorbed only by interstellar material.

The optical depths at line center and the velocities derived from the absorption lines (§3.2) are not affected by the uncertainties in interstellar and/or circumstellar absorption. The reduction of the

![Graph showing details of Chandra spectra of day 39.7 for high-flux (solid line) and low-flux (dashed line) phases, plotted in velocity space for the lines indicated in the legends of each panel. The absorption lines are blueshifted by the same amount in both spectra.](image)
velocities is due to observing deeper into the flow at the time of the later observation.

Our absorption-line model can be improved beyond the results presented in Table 2. First, we need to include the instrumental line profile in order to explore the line widths. From our conclusion in § 3.4 we can define the boundary condition that the emission-line components are at their rest wavelengths, which leads to a reduction of the uncertainties of the other parameters. Our above conclusion that the soft emission lines likely originate from the shock has to be accounted for by not allowing self absorption. We repeated our models without self absorption and found similar results, such that our results are robust.

The issue of the appearance of P Cygni type profiles on day 39.7 cannot fully be answered at this stage. The shape of the absorption lines is not typical for P Cygni profiles, which usually show a sharp blue edge which represents the terminal velocity of the wind. Our finding of symmetric absorption lines indicates that we are not observing the entire velocity profile but only a fraction of it. These plasma regions that reside at the terminal velocity (in velocity space) could be optically thin and thus contribute little to the absorption lines. In the same way, this plasma may also be too thin to produce measurable emission lines, that would be scattered into our direction from the photoexcited plasma moving perpendicularly to the line of sight, further supporting our above conclusion that the soft lines originate from the shock. Also, the He-like resonance lines are expected to be significantly stronger than the intersystem lines if photoexcitation of the circumstellar material was dominant.

The high degree of variability during the first week of the SSS phase (including our observation on day 39.7) is a new discovery that has not been observed in any other nova. However, we have never had the same frequency of observations of the same event. In one case, V4743 Sgr (Ness et al. 2003b), a decline of X-ray brightness occurred, which may be a similar phenomenon. Although this decay is only seen during the first of four observations taken during the SSS phase, it is not known when the SSS phase started, and thus how early in the SSS evolution the decline was observed. Variability was also observed in V1494 Aql, V4743 Sgr, and V832 Bel, but the amplitude was much lower and the variations were periodic (e.g., Ness et al. 2003b; Drake et al. 2003).

In our Chandra observation on day 39.7 we discovered the hardness ratio light curve lagging behind the total light curve by 1000 s. The hardness ratio is commonly used as a temperature indicator. If the temperature varies, then this leads to an increase in brightness before the spectral hardness increases. Temperature variations could occur periodically, but we did not detect any periods in the observation on day 39.7. With the existing observations, we cannot exclude the presence of any periods longer than 3 hr or shorter than a few days. However, photoionization of oxygen could also lead to the higher hardness ratios, as ionized oxygen allows more hard emission to pass through. In this case the material in the line of sight responds to the brightness of the continuum emission by adjusting the degree of ionization within 1000 s. This timescale would be the same for ionization and recombination and implies a density of the absorbing material of \( \sim 10^{10} \text{cm}^{-3} \). This is consistent with the densities derived from the He-like triplets, and the changes in hardness can therefore be explained by variations in the degree of ionization of the circumstellar material. However, this does not explain the origin of the brightness changes.

The spectra extracted from two different time intervals during the episode of high-amplitude variations show complex changes. We found deeper absorption lines and a deeper oxygen edge during times of brighter continuum emission. This shows that the brightness variations are correlated to the absorption behavior of the expanding shell and the surrounding material and each spectrum must be treated independently.

As an example, we applied our model from § 3.2 to the two spectra presented in § 3.5 and found higher column densities during the high-flux phase while the velocities were the same for both spectra. Higher column densities arise when we either look deeper into the outflow (longer path length) or when the density is higher (or both). The high-flux phases can have their origin in a reduction of the opacity, allowing us to view deeper into the outflow where more emission is produced, the densities are higher, and the temperatures are higher.

Most of our results are based on preliminary models, and we are improving these models. The first steps will have to improve the atmosphere and the model for interstellar and circumstellar absorption. The stellar atmosphere has to be modeled as an expanding atmosphere with PHOENIX (e.g., Petz et al. 2005). The O edge has not been explored much, and new models have to be developed (see, e.g., Paerels et al. 2001). We will further improve our model that fits the absorption and emission lines simultaneously (R. A. Schönrich et al. 2007, in preparation). With improved models in place, the changes of temperatures, luminosities, and absorption behavior during the phase of extreme variability can be determined. A separate analysis of the emission lines and continuum produced in the shocked plasma is under way (J. U. Ness et al. 2007, in preparation), and more detailed hydrodynamic models are being developed for comparison with the data (see, e.g., Vaytet et al. 2007). Finally, the Swift spectra can be used to constrain the evolution between the grating observations. The model parameters obtained from grating spectra on days 37.9, 54.0, and 66.9 can be interpolated for days on which Swift spectra are available. The spectral models obtained from the interpolated parameters have to agree with the respective measured Swift spectra.

5. SUMMARY AND CONCLUSIONS

The X-ray grating spectra of the SSS phase are complex and contain a great deal of information. The objective of this paper is to provide an overview of the physical information that can be obtained from X-ray data. We have found the following:

1. The brightness changes between the three observations are consistent with the variations measured from the Swift observations at the same epochs.
2. Short-period oscillations (\( \sim 35 \text{ s} \)), first detected in some of the Swift observations, are confirmed. We discovered that this period resides in the plasma that emits the SSS spectrum.
3. The episode of high-amplitude variations detected with Swift that occurs on timescales of days is accompanied by variations on timescales of hours.
4. The depth of the \( \text{O} \) absorption edge is variable, yielding the lowest optical depth on day 54.0. One possible explanation is photoionization of the absorbing material in the line of sight.
5. The absorption lines are shifted by \( -1286 \pm 267 \text{ km s}^{-1} \) on day 39.7 and \( -771 \pm 65 \text{ km s}^{-1} \) on day 66.9.
6. Declining emission from the shock is observed in the form of collisionally excited emission lines shortward of the SSS continuum. These lines are slightly blueshifted.
7. Superimposed on the SSS spectrum are emission lines whose origin could either be from the shocked plasma or from photoexcited material in the outer regions of the outflow.
8. Intersystem lines from He-like ions are found at their rest wavelengths. The ratio \( i + f \) / \( r \) (the \( 1s - 2p \) resonance line) is greater than one, indicating contributions from recombination.
into excited states and small contributions from resonance scattering. The ratio $f/\gamma$ indicates either densities in excess of $10^{11}$ cm$^{-3}$ or a short distance between the plasma containing the He-like ions and a source for UV radiation.

9. The brightness changes during the phase of variability induce changes in spectral hardness, retarded by 1000 s. Absorption lines and the O edge are deeper during high-state phases, and if the density of the absorbing material is of order $10^{10} - 10^{11}$ cm$^{-3}$, then the hardness changes can exclusively be explained by ionization. In that case the increases and reduction of brightness occur underneath the absorbing material, possibly in the regions where nuclear burning takes place.

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