EVOLUTION OF X-RAY SPECTRA AND LIGHT CURVES OF V1494 AQUILAE

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ABSTRACT

We present six Chandra X-ray spectra and light curves obtained for the nova V1494 Aql (1999 No. 2) in outburst. The first three observations were taken with the Advanced CCD Imaging Spectrometer (ACIS-I) on days 134, 187, and 248 after outburst. The count rates were 1.00, 0.69, and 0.53 counts s–1, respectively. We found no significant periodicity in the ACIS light curves. The X-ray spectra show continuum emission and lines originating from N and O. We found acceptable spectral fits using isothermal APEC models with significantly increased elemental abundances of O and N for all observations. On day 248 after outburst a bright soft component appeared in addition to the fading emission lines. The Chandra observations on days 300, 304, and 727 were carried out with the High Resolution Camera/Low Energy Transmission Grating Spectrometer (LETGS). The spectra consist of continuum emission plus strong emission lines of O and N, implying a high abundance of these elements. On day 300, a flare occurred and periodic oscillations were detected in the light curves taken on days 300 and 304. This flare must have originated deep in the outflowing material since it was variable on short timescales. The spectra extracted immediately before and after the flare are remarkably similar, implying that the flare was an extremely isolated event. Our attempts to fit blackbody, cloudy, or APEC models to the LETGS spectra failed, owing to the difficulty in disentangling continuum and emission-line components. The spectrum extracted during the flare shows a significant increase in the strengths of many of the lines and the appearance of several previously undetected lines. In addition, some of the lines seen before and after the flare are not present during the flare. On day 727 only the count rate from the zeroth order could be derived, and the source was too faint for the extraction of a light curve or spectrum.

1. INTRODUCTION

When hydrogen-rich material is lost by a low-mass main-sequence star and accretes onto a white dwarf (WD) primary in a cataclysmic variable (CV), it settles onto the WD and eventually the bottom of the accreted layer becomes degenerate. When enough material has accumulated and the temperatures become high enough, a thermonuclear runaway is initiated and a classical nova (CN) outburst results. There is an initial short phase of X-ray emission, which quickly fades as the ejecta expand and become optically thick. When the ejected shell expands and cools enough to become again transparent to X-rays, a soft, luminous X-ray source is typically observed, although, each CN evolves differently in X-rays. This phase of evolution in X-rays is called the super-soft X-ray sources (SSS) phase because X-ray spectra at this time resemble those of the class of SSS (Kahabka & van den Heuvel 1997).

V1494 Aql was discovered in the optical by Pereira (1999) on 1999 December 1.785 at $m_v \cong 6$ (Pereira 1999) and reached maximum light in the optical 2 days later, on 1999 December 3.4 at $m_v \cong 4.0$. It subsequently declined by 2 mag in 6.6 ± 0.5 days thus classifying V1494 Aql as a fast nova (Kiss & Thomson 2000). The distance to the nova was determined to be 1.6±0.2 kpc by Iijima & Esenoglu (2003) and an orbital period of 0.13467 days has been suggested by Retter et al. (2000). The hydrogen column density was estimated to be $N_H \approx 4 \times 10^{21}$ cm–2 by Iijima & Esenoglu (2003) from sodium lines in the optical.

X-ray spectra were taken with Chandra, and Krautter et al. (2001) reported that the early evolution showed only emission lines, but that by 2000 August 6 the spectrum had evolved into an SSS spectrum. They also reported an X-ray burst occurred (flare) and the presence of oscillations in one of the grating observations taken during the SSS phase. A detailed timing analysis was presented by Drake et al. (2003).

We re-extracted all Chandra observations, and here we present the light curves and X-ray spectra. We carried out timing analyses, searching for periodic behavior in all observations. We present spectral modeling of the early observations that contain emission lines (Krautter et al. 2001) and provide a qualitative description of the SSS spectra. We also investigated spectral changes from spectra extracted before and after the flare event.

In the next section, we present the observations and explain the extraction techniques. We then focus on the timing analysis in Section 3 and the spectral analysis in Sections 4 and 5. We discuss spectral models in Section 6 and summarize our results in Section 7.

OBSERVATIONS AND IMAGE REDUCTION

We present six observations of V1494 Aql taken with Chandra in 2000 and 2001. Table 1 gives the start date of the observations, the number of days since outburst, instrumental setup, observation identification number (ObsID), exposure time, net count rate, and net count rate for “soft” photons with an energy less than 0.6 keV. The first three observations were taken with the S-array of the Advanced CCD Imaging Spectrometer (ACIS-S), which is an array of CCD chips providing moderate spectral resolution in the energy range 0.2–10 keV. After the SSS was...
detected with the ACIS observation taken on day 248 (Krautter et al. 2001), the next observation used the High Resolution Camera (HRC-S) in combination with the Low Energy Transmission Grating Spectrometer (LETGS), yielding higher spectral resolution. While the HRC detector has no energy resolution, the LETGS disperses the incoming light and projects a dispersed spectrum onto the HRC. LETGS spectra are extracted in wavelength units (range 1–170 Å), but for consistency with the ACIS spectra we converted the LETGS spectra to energy units.

We carried out the reduction with the Chandra-specific CIAO software suite, version 3.3. Since the CIAO standard data processing procedures (the “pipeline”) have changed since the time of the observations, we began our treatment of the images with the level 1 event files which were taken from the Chandra archives along with the accompanying calibration files. With the newest or most applicable calibration routines the exposures were reprocessed mimicking the pipeline reduction using standard routines from CIAO version 3.3.0.1 (Fruscione et al. 2006). These newly constructed event 2 files were used to create our light curves and spectra.

The light curves were extracted using tools developed by Ness et al. (2007a), which determine point-spread function (PSF) corrected source count rates. The PSF for each observation was constructed by following the CIAO threads and are specific to observation, detector location, and energy (Fruscione et al. 2006). The light curves extracted from the ACIS and the nondispersed photons in the LETGS observations (zeroth order) were extracted in 20 s time bins from a source extraction region of 20 pixels. This region encloses 99% of the ACIS PSF and 98% of the HRC PSF. The spectra were extracted from the level 2 event files following the CIAO threads. The ACIS spectra were extracted using a 20 pixel radius circular source extraction region and the LETGS spectra were obtained from the combined ±1 spectral orders.

In order to analyze the burst reported by Drake et al. (2003), we applied a time filter to the data set taken on day 304 using the same time limits for the start and end time of the flare. This separation was done with the level 1.5 event files instead of the level 2 files so that the correct good time intervals could be applied. After this separation we had a pre-flare observation with an exposure time of 8.4 ks, a 1.8 ks exposure of the flare, and a post-flare exposure of 8.0 ks. Each of these three event files were processed by the same reconstructed pipeline as described above to produce the new level 2 event files and spectra.

We expect pileup to not be a problem since the ACIS-S exposures were reprocessed mimicking the pipeline reduction using standard routines from CIAO version 3.3.0.1 (Fruscione et al. 2006). The light curves extracted from the ACIS and the nondispersed photons in the LETGS observations (zeroth order) were extracted in 20 s time bins from a source extraction region of 20 pixels. This region encloses 99% of the ACIS PSF and 98% of the HRC PSF. The spectra were extracted from the level 2 event files following the CIAO threads. The ACIS spectra were extracted using a 20 pixel radius circular source extraction region and the LETGS spectra were obtained from the combined ±1 spectral orders.

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We expect pileup to not be a problem since the ACIS-S observations were designed to minimize this effect by placing the target approximately 7′ from the aim point and reducing the duration of each exposure to 0.8 s. While PIMMS simulations show a small amount of pileup (∼20%) this is an overestimate since PIMMS does not model off-axis pointing.

### 3. PHOTOMETRY

The light curves for the ACIS observations are given in Figure 1, and those for the LETGS observation in Figure 2, both plotted with error bars. The ACIS data show the total count rate dropping as the nova evolves (see Table 1). The count rate drops by 31% between the first two observations. On day 248 the SSS spectrum emerged (Krautter et al. 2001; see also Figure 5), but the total count rate had declined by 16% compared to day 187.

While V1494 Aql was detected on day 727 (Ness et al. 2007a), only the count rate from the zeroth order could be determined, and the source was too faint for the extraction of a spectrum or reliable light curve. Thus, ObsID 2681 is not further considered.

The timing analysis was done using the methods of Horne & Baliunas (1986) which constructs a periodogram, normalized by the total variance, through Fourier analysis which is suitable for evenly or unevenly spaced data. Normalizing by the total variance of the data allows one to calculate a “False Alarm Probability” (Scargle 1982) to aid in identification of false period detections. We examined periods ranging from twice the bin size to half the observation length. Periodograms were constructed for each observation while several versions were

### Table 1: Observation Log

| Start Date (UT) | Days After Outburst | Detector/Grating | ObsID⁴ | Exposure (ks) | Count Rate³ (photons s⁻¹) | "Soft" Count Rate³ (photons s⁻¹) |
|----------------|---------------------|------------------|--------|--------------|---------------------------|-------------------------------|
| 2000 Apr 15, 01:01:27 | 154 | ACIS-I/none | 959 | 5.6 | 1.0 | 0.12 |
| 2000 Jun 7, 02:48:14 | 187 | ACIS-I/none | 89 | 5.2 | 0.69 | 0.07 |
| 2000 Aug 6, 22:02:05 | 248 | ACIS-I/none | 2079 | 5.6 | 0.53 | 0.32 |
| 2000 Sep 28, 06:50:09 | 300 | HRC-S/LETGS | 2308 | 8.1 | 0.65 | - |
| 2000 Oct 1, 10:07:52 | 304 | HRC-S/LETGS | 72 | 18.2 | 0.84 | - |
| | | Pre-flare | 8.4 | 0.71 | - | - |
| | | Flare | 1.8 | 3.17 | - | - |
| | | Post-flare | 8.0 | 0.74 | - | - |
| 2001 Nov 28, 10:37:38 | 727 | HRC-S/LETGS | 2681 | 25.8 | 0.003 | - |

**Notes.** ¹ Observation identification number. ² Zeroth-order count rate over entire bandpass. ³ Count rate for photons of energy less than 600 eV.
analyzed for the observation containing the flare. We checked the data set from day 304, ObsID 72, for periodicity over the whole observation with the flare removed, only the pre-flare segment, and only the post-flare segment.

As seen in Figure 3, none of the ACIS light curves show strong evidence for periodicity. The strongest signal corresponds to a false alarm probability of 42% (day 187 at ∼95 s). The LETGS data, on the other hand (see Figure 2), show periods with false alarm probabilities well below 0.1%, indicating a real signal, for each of the observations. In Figure 4, we show the periodograms of the HRC data with all peaks labeled whose signal strength relates to a false alarm probability less than 1%. The flare is double peaked with additional structure. For further information the reader is directed to Drake et al. (2003).

We detected signals close to the 2500 s period reported by Drake et al. (2003) in all of the grating data. None of those data showed any significant evidence for periods shorter than ∼1200 s (longer than 8.33 × 10⁻⁴ Hz), so this region is not plotted. For the data from day 300, the ∼2500 s signal was the only one detected although the data from day 304 also showed several other strong features. The pre-flare periodogram shows features at ∼1740 s and ∼3600 s, while the post-flare has signals at ∼1200 s and ∼4300 s. The 1200 s signal could be a spectral leakage from both the 3600 s and 2500 s signals, while the 1740 s feature could be a leakage from the 3600 s feature. We also searched for longer period signals in the entire exposure taken on day 304 with the flared portion removed. No longer period signals were seen but the 2500 s and 3600 s features were reproduced while neither the 1200 s or 1740 s features were present.

We are unable to test for the presence of the orbital period of 3.23 hr (=11.6 ks) suggested by Retter et al. (2000), because with our exposure times we cannot sample any periods longer than 9 ks.

The short duration of the flare, along with its photometric variability imply that the source region of this flare must be associated with the hot WD. Variability on timescales of 200 s (the width of one peak during the flare and 10 times our temporal bin size), yields a flare source region physical size of approximately 0.4 AU. While this size is far larger than either a WD or that of the binary system, it is much smaller than the radius of the ejecta after 300 days of expansion.

4. ACIS SPECTRA

The first spectrum, taken on day 134 (top panel of Figure 5), shows the presence of N vii and O viii emission lines at 500 and 650 eV. The O viii line is stronger than the N vii line. In addition, continuum emission, unresolved lines, or the combination of both can be identified up to about 2 keV. By day 187, the lines of N vii and O viii as well as the continuum emission have weakened, but the relative strengths of the N vii and O viii lines seem unchanged. We see no evidence for the appearance of any new features and no excess emission at energies below 600 eV. The decline in the emission line strengths agrees with the reduction in count rate from the photometric data.

The spectrum from day 248 shows further weakening of the O viii line and the possible emergence of a blend of Ne ix lines at ∼900 eV. In addition, a new bright feature appears at energies just below the N vii emission line at 500 eV. As seen in the photometry described in Section 3, the reduction in count rate is caused by the reduction of high-energy continuum emission.
This reduction occurs in spite of the increase in count rate from below ∼600 eV, probably caused by the appearance of the SSS (Krautter et al. 2001). We tentatively interpret this feature as evidence that the density of the ejecta has declined, becoming optically thin to low-energy X-rays. We note, however, that the spectral resolution of the ACIS detector at low energies is limited by the quantum efficiency, and for studies of the soft component the LETGS is better suited.

5. LETGS SPECTRA

Day 300 shows emission lines sitting on top of a continuum, see the top panel of Figure 6. This arrangement makes disentangling the continuum from the lines and line identifications difficult. As a result, we can only make qualitative arguments in this analysis. Table 2 gives a list of all the possible line identifications for the LETGS data along with the associated wavelength, energy, and atomic transitions (lower–upper states). Several unidentified lines exist between 400 and 500 eV, a characteristic that was also seen in the recent nova RS Oph as discussed by Nelson et al. (2008) and Ness et al. (2009).

We see lines from O viii, C vi, and N vi as well as several unidentified lines. While the line at ∼500 eV could be N vii, we interpret this line as N vii due to the presence of the N vii He-like γ (1s–4p) and δ (1s–5p) lines and the absence of the N vii β (1s–3p) line at 640.5 eV. The strongest line in the spectrum taken on day 300, at 442 eV, is an unidentified line. There are also unidentified lines at ∼383, 393, 397, 404, 449, and 482 eV, as well as several other possible weak lines throughout the spectrum. The energy of the O viii line (656 eV) is well above the Wien tail of the continuum (∼530 eV) and can therefore not be photoexcited. At least one line must therefore be purely collisional. Since the O viii line is much weaker than the lines at lower energies, it is reasonable to assume that the stronger lines are a mixture of radiative and collisional excitations.

We constructed three sets of data from the observation made on day 304, as discussed in Section 2, and their spectra are also presented in Figure 6. The second panel shows the pre-flare spectrum, the third shows the flare spectrum, and the fourth...
shows the post-flare spectrum, each plotted with error bars and labels for the most likely line identifications. The spectrum during the pre-flare period again shows emission lines on top of a continuum. However, there is stronger emission from N vi at 430 eV and 498 eV but lines from O vii at 571 eV and C vii at 367 eV were weaker than 4 days prior. The other lines, including all the unidentified lines, do not appear to significantly change in strength when compared to day 300.

In order to isolate the spectrum of the flare, we subtracted the count rate spectra from before and after the flare from the data recorded during the flare event. The bottom panel of Figure 6 shows the difference spectrum from before and after the flare (in units of count rates per keV). This difference spectrum allows us to identify in which way the flare may have altered the emitting plasma in ways such as heating or photoionization. Examining the plot, we see that the flare event had little effect on the spectrum, yielding essentially the same spectrum as before the flare. This means that the difference between the pre-flare and post-flare count rate spectra yields the emission that originates from the plasma that emits the flare. This flare-only spectrum is shown in the third panel and an emission line spectrum with little or no sign of a continuum can be seen. During the flare the count rate in the 449 eV unidentified line, which was the strongest feature in the day 300 spectrum, doubles and there are also increased count rates for the unidentified lines at 393 eV, N vi at 430 eV, C vii at 459 eV, and N vi at 498 eV. Also, unidentified lines appear at 405 and 475 eV that were not seen in any of the other spectra. The unidentified line at 442 eV is weak during the flare, while the C vii 435 eV line and the unidentified line at 482 eV are not seen in the flare at all.

After the flare event, most of the lines appear to return to near their initial pre-flare level. There is a slight increase in the strength of the N vii 420 eV line as well as in the 383 and 393 eV unidentified lines but no strong changes are seen in any of the other N vi lines. A significant portion of the total difference shown in the bottom panel of Figure 6 comes in the wings of the unidentified lines at 442 and 449 eV. There is a small increase in emission on either side of these lines after the flare but there is no difference in the strength of the peaks. This may be due to some change in the continuum or an increase in the temperature. There is also a small amount of emission seen post-flare at 475 eV, which must be residual from the flare. Unfortunately, the flare-only spectrum is not well enough exposed to detect any changes in the continuum level, because the flare lasted only a short time (Drake et al. 2003). If the flare-only spectrum is primarily an emission line spectrum, then the flare could originate from the same regions that emit the emission lines that blend with the continuum from the white dwarf. This would imply that two physically distinct components are present. In view of the short timescales of the flare, the regions that produce the emission line component could be rather compact.

Another possibility could be that holes in the ejecta temporarily allowed more ionizing continuum emission to reach the surrounding medium and increase the degree of ionization. This would lead to stronger emission lines, while some of the ionizing continuum emission could be radiating into a different direction than the line of sight. We emphasize, however, that the data are too limited for any strong conclusions, and these suggestions are thus highly speculative.

6. SPECTRAL MODELS

In this section, we describe our attempts to find suitable spectral models. We started with the ACIS spectra and fitted isothermal APEC models (Smith et al. 2001). The best-fit parameters for the models shown in Figure 5 are given in Table 3 for each observation. In order to achieve satisfactory fits to the data, high abundances of N and O are required. While high abundances of N and O are not unusual in novae, the amount by which these elements have to be increased appears rather unrealistic (see, for example, the compilation of model predictions and observations of typical nova abundances listed by Jose & Hernanz 1998; Table 5). The best-fit models require an oxygen abundance that is 20–30 times solar and a nitrogen abundance of several hundred times solar. We stress that, in addition to the quoted statistical uncertainties, there are significant sources of systematic uncertainties. We estimate the greatest source of uncertainty is the assumption of an isothermal plasma while the temperature structure of the emitting plasma is likely more complex, implying high- and low-temperature plasma. Since the O and N lines are formed at temperatures significantly below the temperatures of the isothermal model (see Table 3), these lines are formed rather inefficiently in this model. The only way to reproduce these lines and the high-energy emission at the same time is to increase the O and N abundances. A two-temperature model with a cool and a hot component yields lower N and O abundances (because the N and O lines are formed at low temperatures, while these elements are fully ionized at higher temperatures), however, such a model has more parameters and yields no significant improvement in reproducing the data. Another source of uncertainty is the parameter N_H. Lower values of N_H require less emission at soft energies, thus leading to a higher resultant temperature and higher N and O abundances.

The model shown in the bottom panel of Figure 5 (day 248) consists of an APEC and a blackbody component, however, we only show the APEC component. We found a good fit to the SSS component, yielding a combination of blackbody temperature and luminosity (see footnote in Table 3) that is typically encountered when fitting blackbody curves to the SSS spectra of novae. The N abundance is not constrained, owing to the overlap of the blackbody component with the N vii line.

Based on the blackbody parameters, we have tested an alternative model to the observations taken on days 134 and 187. We have included a blackbody component with the same parameters as those found for day 248. We kept the blackbody parameters fixed and iterated only the APEC model parameters and N_H. We found the surprising result that better fits can be obtained, yielding higher values of N_H (4.4 × 10^{21} cm^{-2} and 5.5 × 10^{21} cm^{-2}, respectively) and a lower APEC temperature. The abundances of N and O are also lower with the two-component model. This result allows the possibility that a SSS component could have been present all the time and was only hidden behind a higher column of neutral hydrogen. However, this exercise also

| Model | Days After Outburst |
|-------|---------------------|
| 134   | 187                 |
| 248   |                     |

| Parameter | Days After Outburst |
|-----------|---------------------|
| kT (eV)   | 630 ± 40            |
| N_H (×10^{21} cm^{-2}) | 3.4 ± 0.3 |
| O abundance (×solar) | 29 ± 6 |
| N abundance (×solar) | 840 ± 150 |

Note. * Plus blackbody with T_{bb} = 31 ± 2 and log(L_{bb}) = 37.7 ± 0.4.
demonstrates the sensitivity of models to such soft spectra to the assumed amount of interstellar absorption. This leads to a large systematic uncertainty that is difficult to assess.

The LETGS spectra are also extremely difficult to model. We first attempted blackbody fits, but we found no satisfactory fits. The problem is that no spectral range can be identified that is free from line emission. We then tried a number of Cloudy models with a wide array of parameters, but none gave satisfactory results. The combination of optically thick plus optically thin plasma emission makes the LETGS spectra of V1494 Aql particularly challenging. A promising approach is to use the PHOENIX atmosphere code, but models for spectra like the ones presented here do not yet exist. Optimization of the code to fit these data is in progress (D. vanRossum & P. Hauschildt 2008, private communication).

7. DISCUSSION AND CONCLUSIONS

The evolution of V1494 Aql underwent two distinct phases. The first phase was characterized by hard X-ray emission, dominated by emission lines. Our APEC fits to the ACIS observations yielded satisfactory results, and the spectra imply that the ejected gas is an optically thin plasma in collisional equilibrium. It is possible that the source of emission is shocks within the ejecta, as has been proposed by O’Brien et al. (1994). Unfortunately, we cannot test the predicted decline in count rate, because the third ACIS observation was contaminated by the rising SSS, leaving us only with the two observations on days 134 and 187. Linear interpolation between these observations suggests a decline rate of 2.1 counts s\(^{-1}\) yr\(^{-1}\). For a strong shock, the post-shock temperature \(T_s\) is given by

\[
T_s = \frac{3}{16} \frac{m v^2}{k},
\]

where \(k\) is Boltzmann’s constant and \(m = 10^{-24}\) g is the mean particle mass, including electrons (see, e.g., Bode et al. 2006). If the observed emission is induced by a shock, then the temperatures derived from the isothermal APEC models (Table 3) correspond to a shock velocity of 700–800 km s\(^{-1}\). In a multitemperature plasma, the hottest component determines the shock velocity (see, e.g., Bode et al. 2006). If our spectra allowed us to resolve more temperature components, the shock velocity derived from the hottest component would be slightly higher (see, e.g., Ness et al. 2009), but not by much, since the average temperature of the isothermal models is dominated by the hottest component. Since these observations were taken more than three months after outburst, significant deceleration will have taken place which explains why these velocities are lower than the early expansion velocities of ~1300 km s\(^{-1}\) found by Moro et al. (1999). However, with only two velocity values, we cannot determine the power-law index for different scenarios.

The second phase is the SSS phase that started some time before day 248 after outburst and overlapped in time with the first phase. Figure 6 shows that some residual emission from the first phase can still be recognized at high energies on days 300 and 304. This is a similar situation to that encountered for RS Oph, where the shock emission was still detectable at high energies, while the SSS spectrum dominated at low energies (Ness et al. 2007b). While the ACIS-S spectrum taken on day 248 shows a typical SSS spectrum, the details revealed by the Chandra grating spectra are remarkably different from what SSS spectra are usually like. For comparison, the SSS Cal 83 was observed with the same instrument, and Lanz et al. (2005) presented spectra that show continuum emission with absorption lines that can be fitted with atmosphere models, but little line emission can be seen. While V1494 Aql was the first CN to have been observed with high spectral resolution in X-rays, later grating observations of novae during their SSS phase revealed spectra more similar to that of Cal 83, e.g., V4743 Sgr (Ness et al. 2003) or RS Oph (Ness et al. 2007b). Those spectra can be fit with stellar atmospheres (Lanz et al. 2005; Petz et al. 2005; Nelson et al. 2008). In contrast, the second-most prominent SSS, Cal 87, is also dominated by emission lines (e.g., Greiner et al. 2004) and may be more similar to V1494 Aql. Since Cal 87 is an eclipsing binary, the viewing geometry may be an explanation for the different X-ray spectra. However, no spectral analysis of the grating spectra of Cal 87 has been presented, likely owing to the same complications that we encountered.

Our photometric analysis revealed that the first phase of the evolution shows no periodic oscillations, while the SSS phase is modulated by short-period oscillations. The absence of such oscillations in the early observations supports the notion that they originate from the WD, which supports the interpretation by Drake et al. (2003) that these are nonradial g\(^{+}\) pulsations.

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