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TV Cassiopeiae with Chandra and XMM–Newton X-ray Observations †

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Abstract: TV Cassiopeia (TV Cas) is a well-known eclipsing Algol-type binary comprising a B9V primary and F7 IV secondary in an orbit with a period of 1.81 days, together with a purported low-mass companion in a wide orbit. Despite the considerable attention TV Cas has received in optical and UV bands, no X-ray analysis has been reported. Chandra has detected TV Cas six times and XMM–Newton observed it twice, all serendipitously during observations of the starburst galaxy IC 10. We have put all the X-ray data together to investigate its coronal morphology and spectral properties. We use the X-ray light curves and eclipses to probe the emitting geometry and the X-ray spectra at different epochs to investigate the activity mechanisms and test speculation that TV Cas undergoes significant mass transfer episodes.

Keywords: TV Cas; eclipsing binary; orbital period variability

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1. Introduction

Algol is a semi-detached binary in which an evolved late-type star fills its Roche–Lobe and an early-type companion accreting matter [1,2]. For the X-ray interest in Algol systems, the early type star is expected to be X-ray dark—too hot for an outer convection zone and too cool for a radiatively-driven shock-excited wind. Chung et al. [3] provide the proof that the X-ray emission of Algol is dominated by the secondary. One exception to this might be if there is Roche lobe overflow from the cooler star. If so, there could be some emission from accretion onto the hot primary. There is not any existing evidence for X-rays coming this on Algol systems, but from H_α [4].

Singh et al. [5] compared the X-ray emission between RS CVn and Algol-type binaries. They found that there is no obvious correlation of X-ray luminosity and Roche-lobe filling fraction in the sample of Algol binaries [6]. Drake [7] has investigated the abundance of Algol B and showed the HR 1099 and Algol during times of quiescence since the light curves are smooth and devoid of obvious flare activity.

Therefore, eclipses are key because we know all the emission is from one star only, and we know the geometry of the eclipse because the binary parameters and inclination are relatively well-constrained.

White et al. [8] suggested that the hotter and cooler plasma are in two distinct regions based on the lack of an obvious eclipse in the harder of two EXOSAT X-ray bandpasses. Culhane et al. [9]

supported this conclusion from a similar EXOSAT observation showing an apparently un-eclipsed hot component on the binary TY Pyx. This fitted well with Owen & Spangler [10] radio result and Swank et al. [11] low-resolution spectra of active stars fitted with discrete two-temperature models including a hard and soft component.

TV Cas is located at RA 00:19:18.74232, Dec 59:08:20.5604. The physical parameters for TV Cas is shown in Table 1, compiled from Erdem [12] and Khalesseh & Hill [13]. Bakos & Tremko [14] has reported the photoelectric light curves of TV Cas (using a photoelectric photometer) and claimed the period is not constant, which indicates that mass exchange is taking place between the two components of the system. de Landtsheer [15] presented four near infrared light curves of TV Cas from the Utrecht photometer equipped with the narrowband (10 nm) Utrecht Photometric System. They used the ephemeris of Margrave [16] *2441595.3582+1.8125944.E* to calculate the Observed-minus-Calculated (O–C)'s.

The analysis of these curves shows that the secondary minimum appears to be at phase 0.502, which indicates that the cool component fills its Roche lobe. The primary minimum is at JD 2444912.

The updated O–C diagram is on the website of the Variable Star and Exoplanet Section of Czech Astronomical Society [17]. From the previous study about the TV Cas eclipsing binary, e.g., [18], it consists of one massive B9V star and a larger, cooler and tidally distorted G5IV-III companion. The components of TV Cas are rotating at less than the synchronous value, and, in particular, the secondary only rotates two-thirds of the rate [12]. The origin of the X-ray emission, whether from one component of the binary system or just from an accretion disk, is unclear.

Table 1. Fundamental parameters for TV Cassiopeia (TV Cas, see Erdem [12] and Khalesseh & Hill [13]).

Massive Star	**B9V**	**Companion**	**G5IV-III [12], F7 IV[13,19]**
$M_{primary}(m_{\odot})$	3.78	$M_{secondary}(m_{\odot})$	1.53
$R_{primary}(R_{\odot})$	3.15	$R_{secondary}(R_{\odot})$	3.29
$T_{primary}$(K)	10500	$T_{secondary}$(K)	5235
$L_{primary}(L_{\odot})$	107	$L_{secondary}(L_{\odot})$	7
inclination	0.013		
distance (pc)	275		

2. Observations

Since the launch of the Chandra X-ray Observatory, TV Cas has been within the Chandra field of view six times. Their observation IDs are: 11080, 11081, 11082, 11084, 08458, and 07082. We use CIAO 4.8 to extract the light curves. First, we use commands *chandra_repro* to process the raw data and *axbary* for the barycentric correction. Since some sources are on the edge of the charge-coupled device (CCD) detector and some are close to the CCD gaps, we manually create the background and source region files. They are shown in Figure 1. The smallest inner green circle (radius of 30″) centered at TV Cas in each panel is the source region, and outer annulus region (between 40″ and 80″) or the big circular region (radius of 80″) is the background. The light curves are extracted with a bin size of 200 s using *dmextract*.

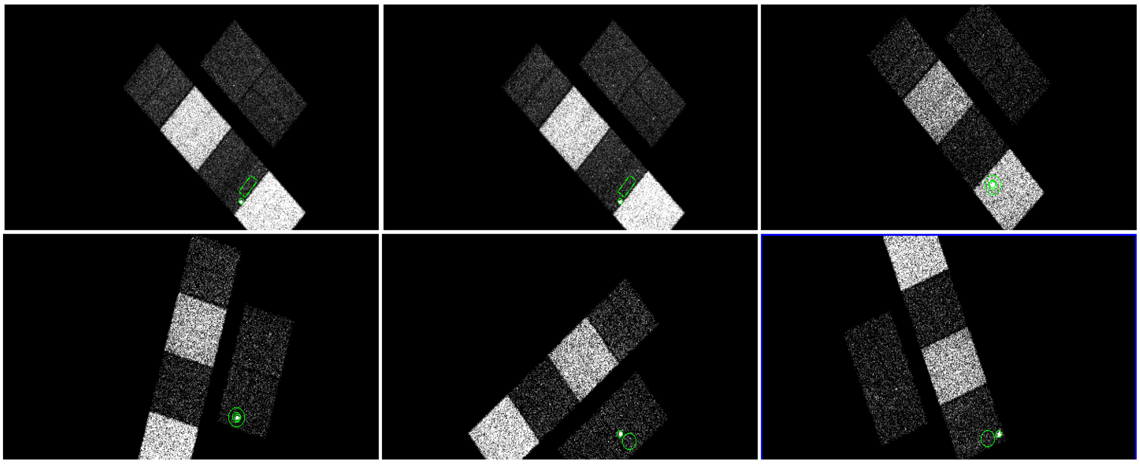

Figure 1. TV Cassiopeia (TV Cas) with the Chandra observations in the order of: 07082, 08458, 11080, 11081, 11082, and 11084. For observation ID 11080 and 11081, the smallest inner circle in green is the source region of TV Cas, and the outer annulus is the background extraction region. Similar to the other 4 observations, just the background region is the big green circle/rectangular.

3. Light Curves and Spectra

We use the X-ray light curves and spectroscopy to investigate the magnetosphere of TV Cas, search for the X-ray eclipse of the binary system that might yield crucial geometric information, and test the hypothesis that the X-rays are a result of the corona of the cool component. From each observation, the light curve of TV Cas is plotted in Figure 2. After combining all six observations, the folded light curve is shown in Figure 3. The X-ray Multi-Mirror Mission (XMM–Newton) observation in 2003 has the longest exposure time. We used the standard procedure (see [20–24]) to extract the source. The folded light curve shows two double peaks and double troughs.

The eclipses of AR Lacertae are like TV Cas except the primary is also a cooler star and an X-ray emitter [25]. We could use the AR Lac light curve to understand the corona structure, and how coronae like those of Algol secondaries can have 10,000 times the luminosity of the solar corona e.g., [26–28]. The relevant quantity for eclipse diagnosis is the scale height of the corona. Basically, to get to be 10,000 times more luminous than the Sun, the star could do one or more of these: (1) cover more of the surface in bright active regions (but this only gets to 100 times); (2) make the plasma more dense (emission proportional to density squared); and (3) increase the height of the emission making the emitting volume much bigger. With eclipses, we can diagnose (3) and with enough S/N begin to investigate (1) and (2).

Both components of TV Cas have radii of $\sim 3R_\odot$. The AR Lac secondary (the K star) is a similar size, with radius $\sim 2.7R_\odot$. From the TV Cas eclipse data, we can see that the depth of the eclipse is about 50%. This implies that the corona is about the same size as the eclipsing star, which is the same size as the secondary itself.

The X-ray spectrum from each of the Chandra observations is shown in Figures 4–9. The fitting parameters are listed in Table 2. We used a photoelectric absorption model with one temperature except observation 07082 using two-temperature fitting as shown in Figure 4. We use the Wisconsin absorption model [29] and two-temperature APEC model (APEC emission spectrum). The parameter nH is the neutral hydrogen column density in units of 10^{22} atoms cm^{-2}. We set the initial temperature as 1 keV, abundance equals 1, redshift is 0, and normalization as 0.01. If we use one temperature for observation 07082, it is $0.051^{+0.009}_{-0.009}$ keV. The spectral model appears similar to a simple model for the corona of the Sun.

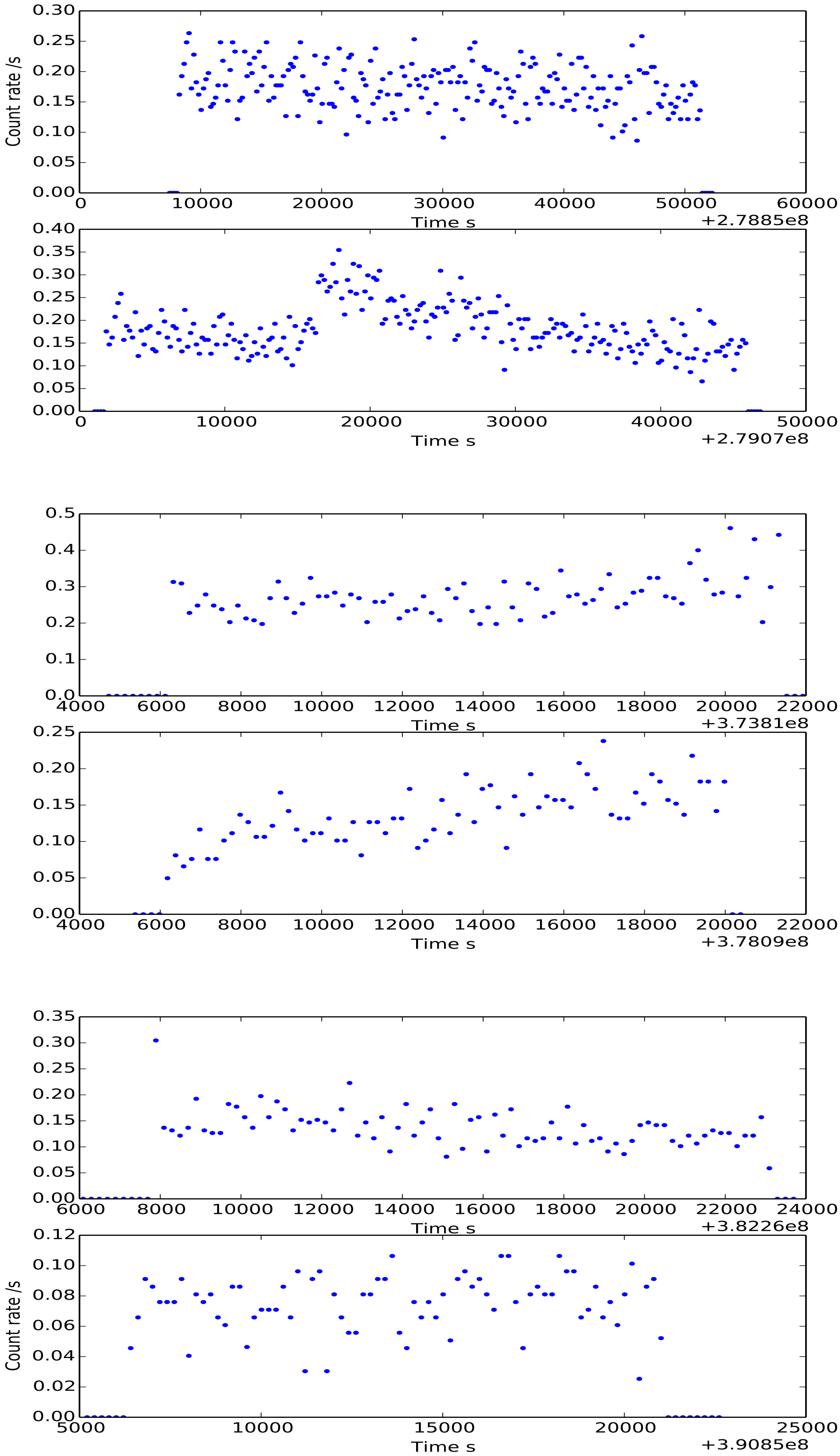

Figure 2. Each panel shows the light curve of TV Cassiopeia from one of the six Chandra observations in the order of: 07082, 08458, 11080, 11081, 11082, 11084. Typical errors of the count rates are $0.02\ \mathrm{s}^{-1}$.

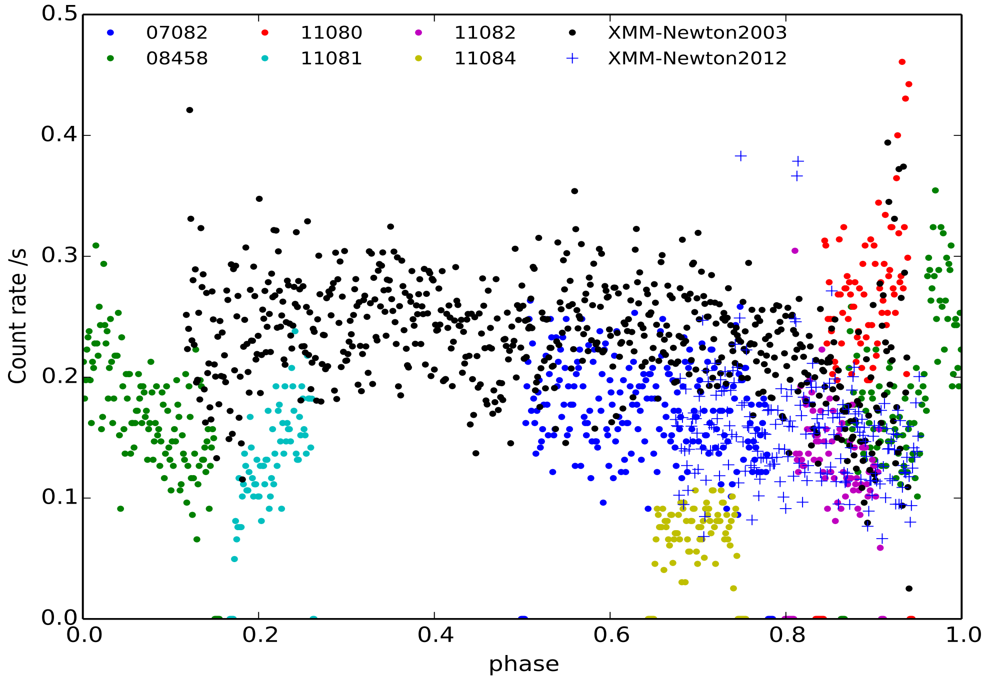

Figure 3. Folded light curve of TV Cassiopeia from six Chandra and two XMM–Newton observations. The orbital period is 1.81260009 days and initial time (phase 0) is 32827.76 in Modified Julian Date. The average size of the error bars is 0.02 s^{-1}.

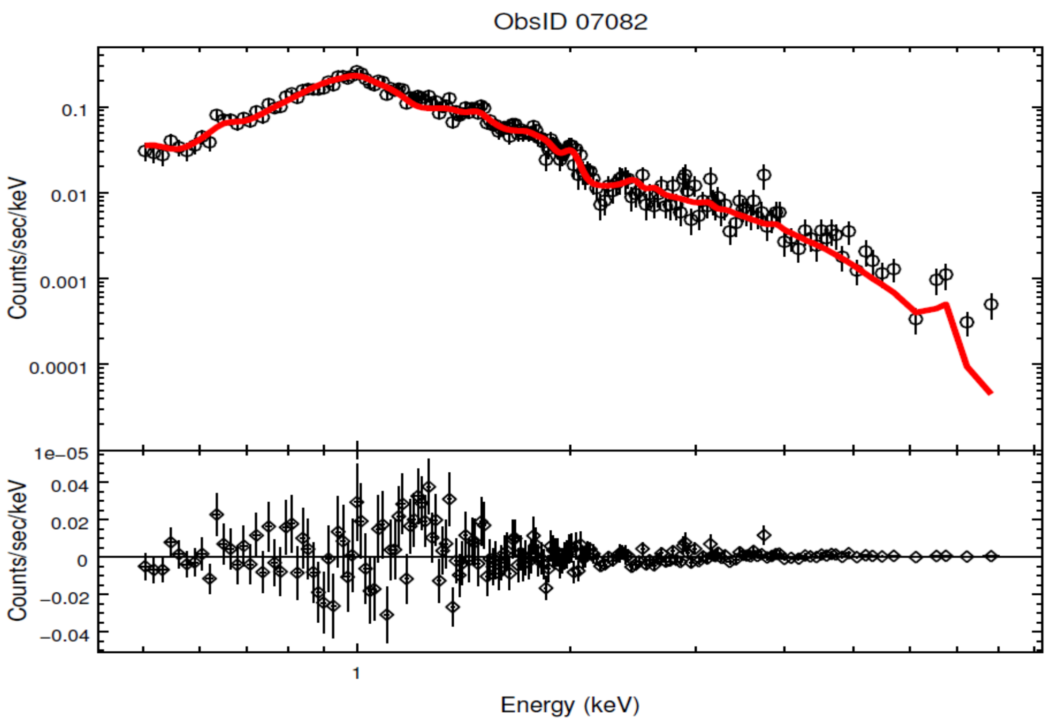

Figure 4. TV Cas Spectrum from Chandra Observation ID 07082.

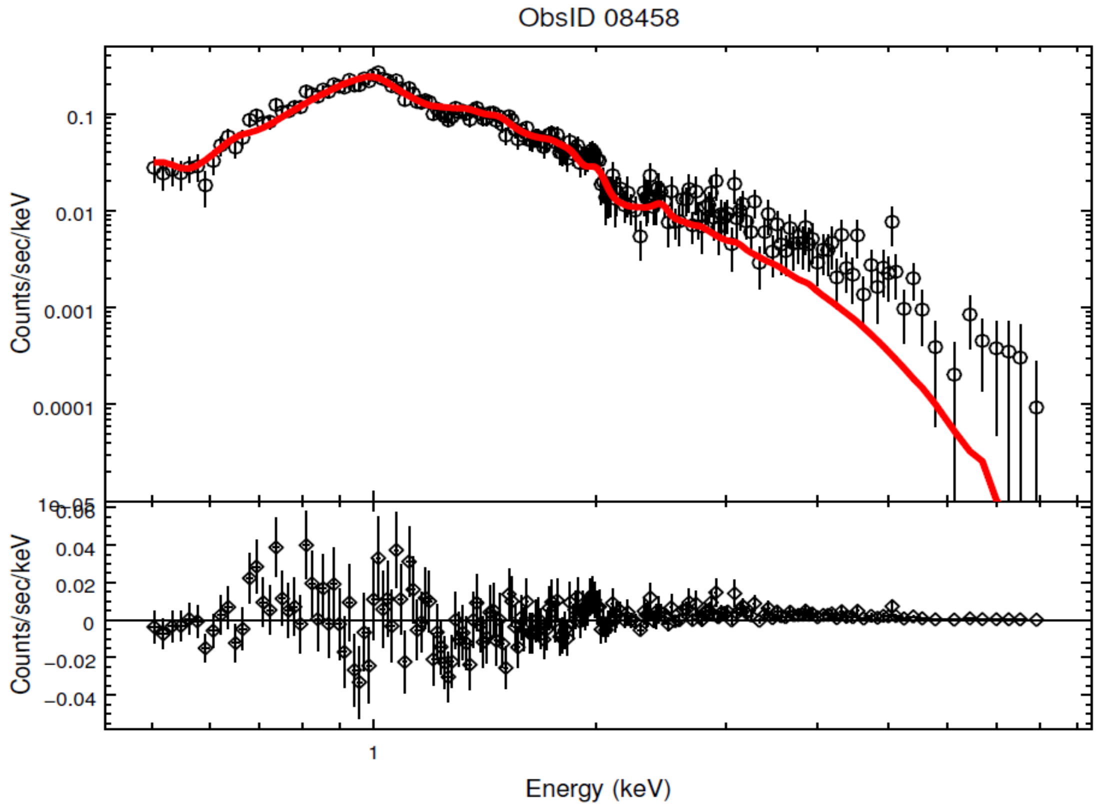

Figure 5. TV Cas Spectrum from Chandra Observation ID 08458.

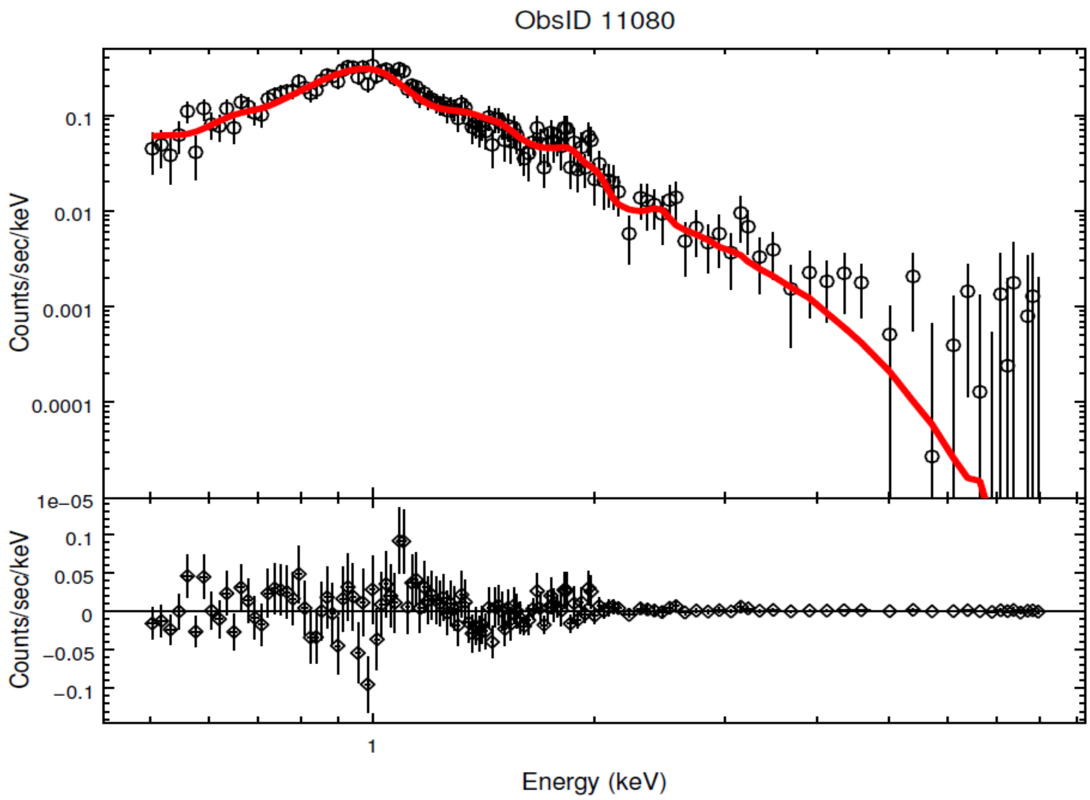

Figure 6. TV Cas Spectrum from Chandra Observation ID 11080.

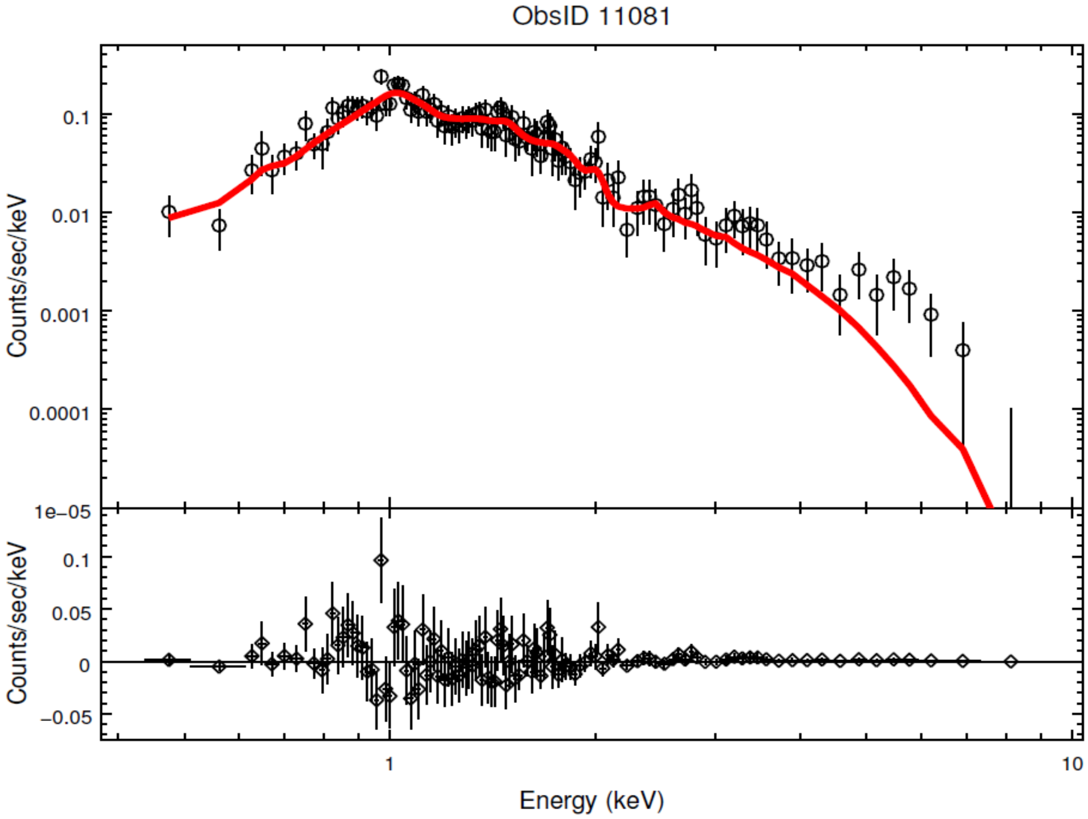

Figure 7. TV Cas Spectrum from Chandra Observation ID 11081.

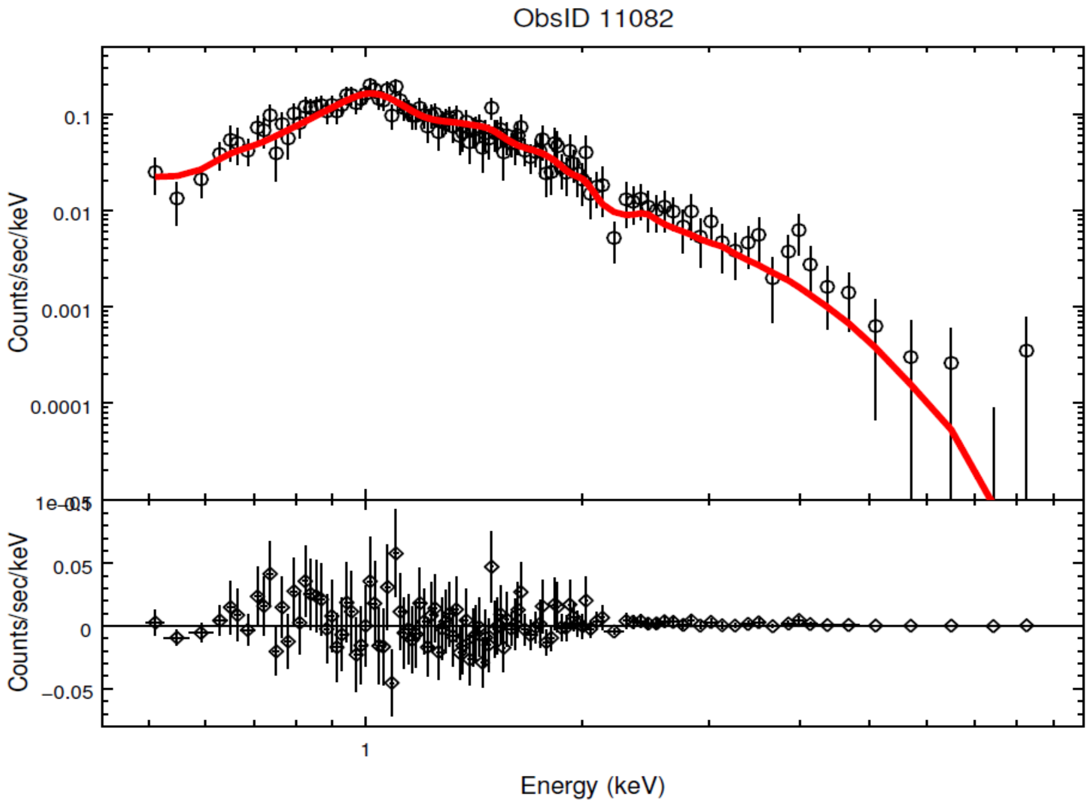

Figure 8. TV Cas Spectrum from Chandra Observation ID 11082.

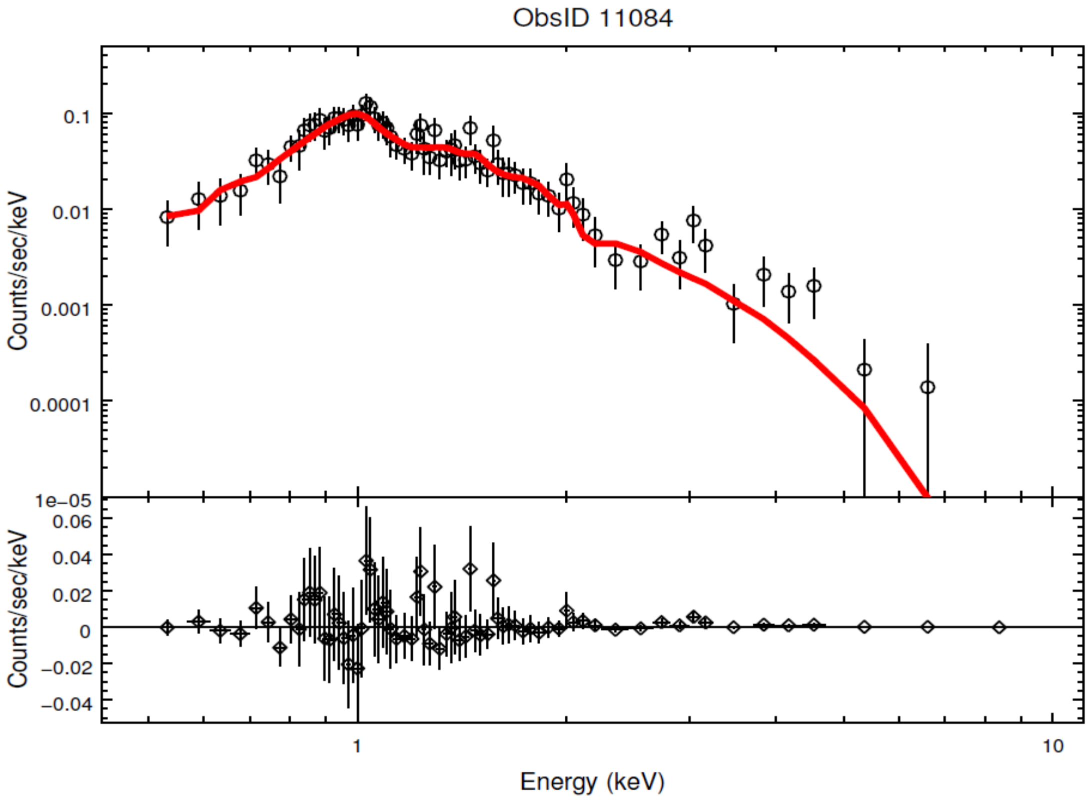

Figure 9. TV Cas Spectrum from Chandra Observation ID 11084.

Table 2. Spectrum parameters for TV Cas.

ObsID	**nH** 10^{22}	**kT** keV	**Abundance**	**Norm**	**Reduced** χ^2 **Statistic**
07082	< 0.021	$2.55^{+0.17}_{-0.15}$	$0.27^{+0.06}_{-0.06}$	$0.0009^{+5.5e-05}_{-6.7e-05}$	1.178
		$1.04^{+0.02}_{-0.02}$		$0.0006^{+0.0002}_{-0.0001}$	
08458	$0.107^{+0.013}_{-0.012}$	$1.059^{+0.017}_{-0.017}$	$0.068^{+0.006}_{-0.006}$	$0.0030^{+0.0001}_{-0.0001}$	1.239
11080	$0.106^{+0.018}_{-0.017}$	$1.042^{+0.023}_{-0.024}$	$0.103^{+0.014}_{-0.013}$	$0.0021^{+0.0002}_{-0.0002}$	0.761
11081	$0.095^{+0.031}_{-0.028}$	$1.285^{+0.051}_{-0.058}$	$0.096^{+0.025}_{-0.022}$	$0.0022^{+0.0002}_{-0.0002}$	0.688
11082	< 0.039	$1.268^{+0.053}_{-0.063}$	$0.102^{+0.029}_{-0.025}$	$0.0017^{+0.0002}_{-0.0002}$	0.581
11084	< 0.097	$1.081^{+0.217}_{-0.055}$	$0.087^{+0.026}_{-0.021}$	$0.0013^{+0.0002}_{-0.0004}$	0.555

4. Discussion

We can use the AR Lac eclipse model to evaluate what a 50% eclipse dip means when it is eclipsed by a star with a radius $\sim 3\ R_\odot$: e.g., Figure 6 of Drake [25]. We want the blue/black curves for when the G star dominates and the K star is relatively X-ray dark (thereby approximating the Algol one). We only care about the eclipse on the right side of each panel. They are all the same from top to bottom (since that direction probes the K star eclipse), and so only want to look at the left to right variation. A 50% eclipse depth is somewhere between the right two panels, and close to the third panel. The scale height (it is an exponential atmosphere there, so scale height is the e-fold height for emission) is 1 $R_\odot$, so the"radius" of that corona is $\sim 2.5\ R_\odot$ (radius of the Algol primary G star is 1.5 $R_\odot$), which is about the same size as the secondary.

Therefore, we get a similar eclipse and it is telling us that the corona on the secondary of TV Cas is of a similar size to the star itself—it looks like a more compact corona in terms of the extension above the stellar surface. The Algol G star corona is about twice as big as the star itself, so something is different. We might expect them to be different because the TV Cas secondary is an evolved F star, and with a somewhat different and thinner (relative to its radius) convection zone (where the magnetic fields are generated).

The highest peaks in the folded light curve of Figure 3 are from the observations 11080 and 08458. The spectra from these two observations show high nH compared to the other four observations. The two dips of the phased light curves are from observations 11081 and 11084, from which their nH in the spectra are low.

For most of the X-ray spectra, we only used one-temperature modeling. The resulting neutral hydrogen column density somehow anti-correlates with temperature. The one-temperature results of these six observations appear bi-polarized, which implies that two-temperature fitting is needed. This paper is just our initial results. In the next step, we would like to improve the modeling and use a two-temperature APEC model to fit all the X-ray spectra. We will also model the phased light curves so that more physical parameters of this Algol-type binary system could be explored.

Conflicts of Interest: The authors declare no conflict of interest.

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