Using Eclipses to Probe the Jets in SS 433 using the *Chandra* High Energy Transmissions Grating Spectrometer

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Abstract and Introduction

The Galactic microquasar SS 433 is the only known astrophysical object to exhibit strong, relativistically red- and blue-shifted lines from elements such as S, Si, Fe, Ni. The X-ray emission lines originate in a bipolar jet outflow that is launched somewhere very close to the compact accretor. The pair of jets travels in opposite directions at 0.26c, and the jets precess with a period of 164 days. During 2018 August 10-14, SS 433 was observed using the High Energy Transmission Grating Spectrometer (HETGS) system on *Chandra*. During this epoch, one 20 ksec "short" observation was made three days before an eclipse of the compact object by the donor, and then a 96 ksec "long" observation started shortly after mid-eclipse. The short and the long observations were designed to take advantage of the eclipse and carry out time-resolved spectroscopy to infer spatial variation of physical properties such as composition, temperature, and density at different distances along the jet. In addition to phenomenological fits to determine the properties of the observed emission lines, here we present results from fitting collisionally ionized plasma models.

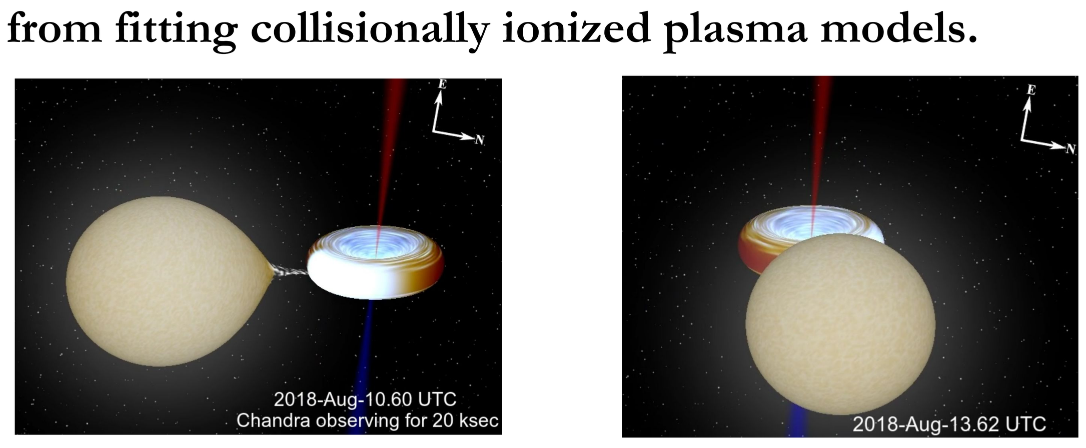

Figure 1.

(a) The geometry of the system at the starting time of the 20 ksec reference observation.

(b) The geometry of the system at the starting time of the 96 ksec eclipse observation. The Western jet was being eclipsed.

Spectra and Phenomenological Modelling

- **Fitting Results:**

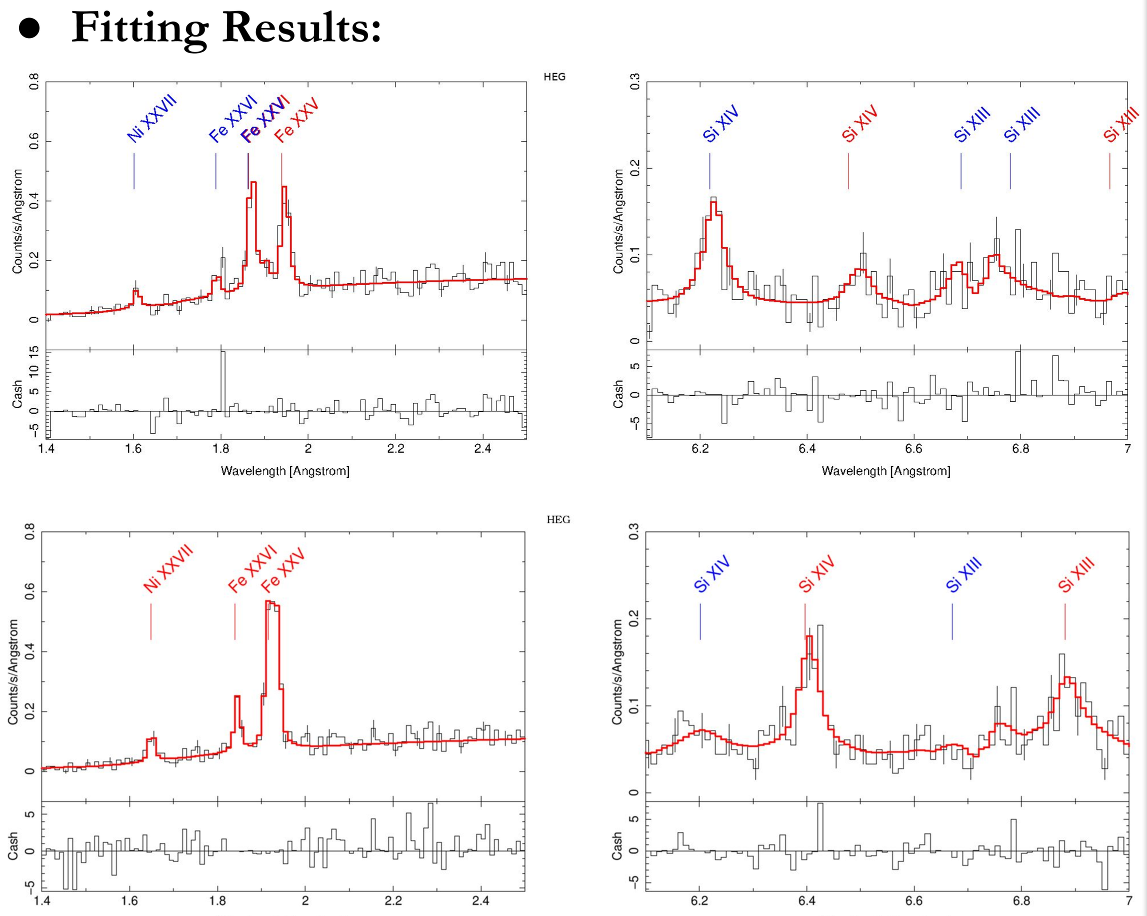

Figure 2. The panels show the 1.4-3.8Å (left) or 6.2-7.0Å (right) for the short reference observation (top) or the first 19.2 ks of the eclipse observation (bottom). Red line: phenomenological best-fit model to the spectra. Line identifications are labeled so that the red characters refer to the emission lines from the Eastern jet while the blue ones are from the Western jet. The Cash statistic residuals are shown at the bottom of each spectrum. It is evident that some of the lines, e.g. Fe XXVI and Fe XXV from the Western jet were blocked during the eclipse.

- **Fitting Method:**

We used a blind fitting method to model the spectra using the Interactive Spectral Interpretation System software (Houck & Denicola, 2000). The underlying continuum was modeled by an absorbed power law and the emission lines modeled as Voigt profiles.

Discrepancies between the Observed and Ephemeris-predicted Redshifts

- **Discrepancies in the Observed Redshifts**

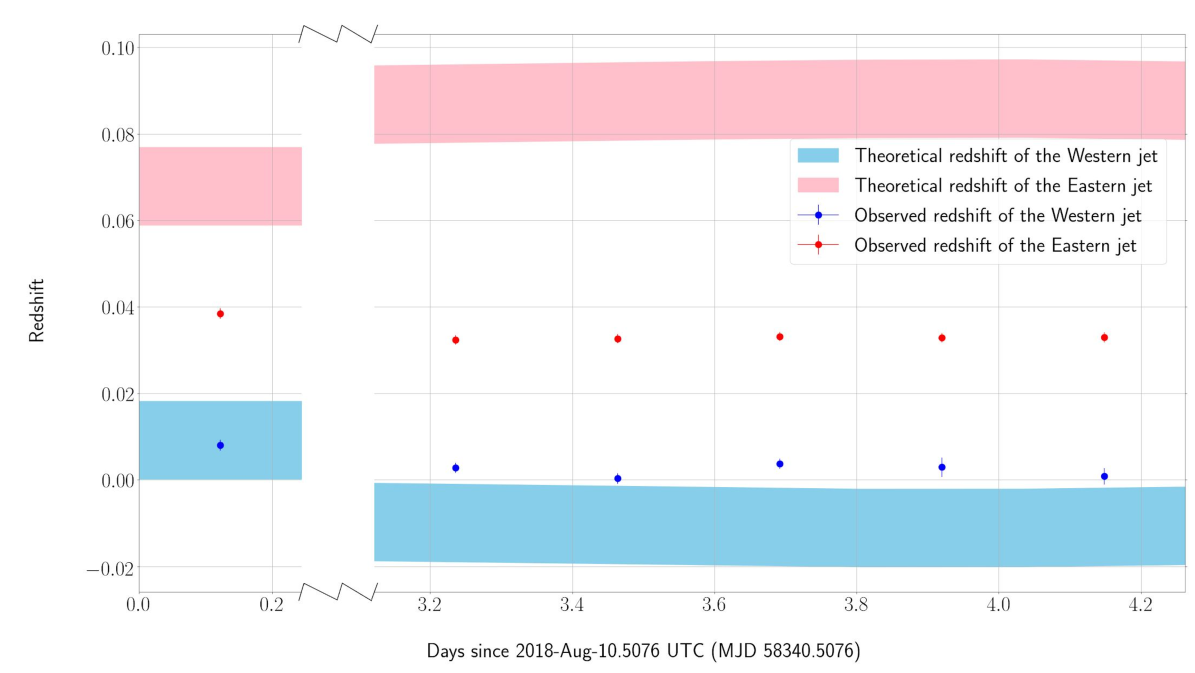

Figure 3. The observed redshifts from the 2018 observations with *Chandra* HETG and the predicted redshift according to the kinematic model. The blue and pink bands around the predicted redshift indicates the nutation motion of the jet.

Evolution of Line Fluxes

We compared the line fluxes between the short observation and the long observation of both Eastern and Western jets.

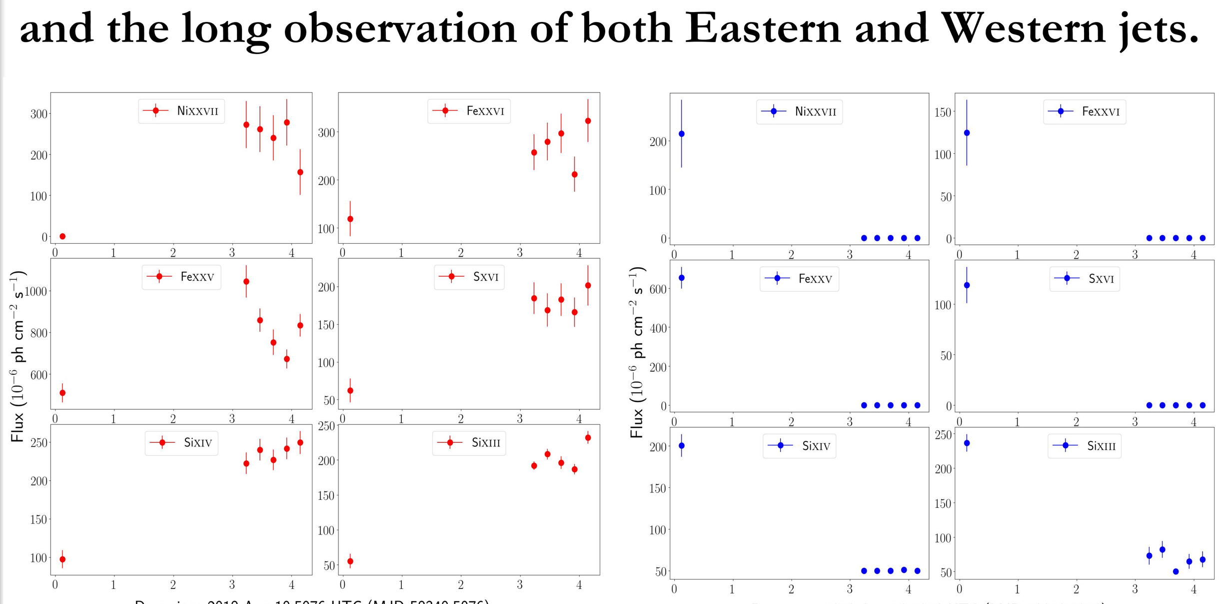

Figure 4. The left and right panel show the flux changes of six prominent emission lines of the Eastern (in red) and Western jet (in blue), respectively, over the short reference and the long eclipse observation.

Plasma Model

We use a plasma diagnostic approach where emission lines correspond to four specific jet plasma temperatures (Marshall et al. 2002). Eastern and Western jets are fitted at the same time using this four-temperature plasma model.

- **Parameter Table for the 20 ksec Reference Observation:**

Table 1. Jet Parameters from a Multitemperature model for the 20 ksec observation

T ($\times 10^6$ K)	n_e ($\times 10^{14}$cm^{-3})	vturb (km/s)	metal ($\odot$ metal)	Ni ($\odot$ Ni)	Western jet EM ($\times 10^{57}$cm^{-3})	Eastern jet EM ($\times 10^{57}$cm^{-3})
6.3	1	1876.6	3.086	42.61	1.86	1.29
12.6	1	1876.6	3.086	42.61	2.09	<0.037
31.6	1	1876.6	3.086	42.61	<0.037	<0.037
126.	1	1876.6	3.086	42.61	10.42	14.16

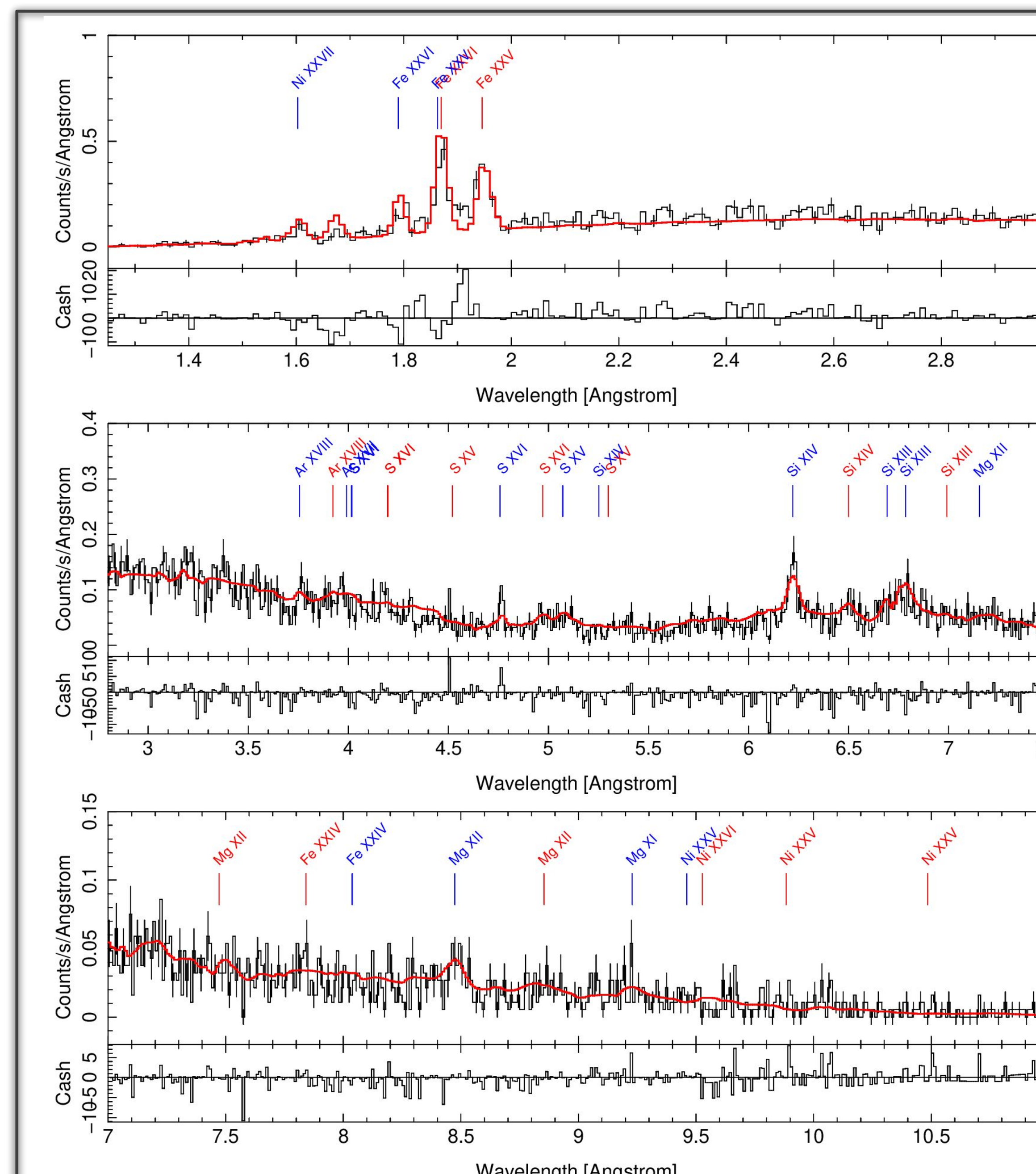

Figure 5. The whole spectrum of the HEG spectra of SS 433 observed during the short reference observation, compared to a plasma model of the spectra of the blue and red jets. Black line: observed spectrum. Red line: four temperature plasma model providing a generally adequate fit to the spectrum. Fe I line is prominent in the residual at 1.93 A.

Summary of the Results

- **Within the long observation, no significant redshifts change were observed for either jet. Given *Chandra*'s spectral resolution, we should have detected a change in redshift as the jets precess. Such behavior was also previously noted by Marshall et al.(2013), and suggests strongly that the inner X-ray jet does not precess smoothly.**
- **While the observed Doppler shifts of the emission lines in the Western jet are close to their ephemeris predicted values, the Doppler shifts of the lines from the Eastern jet differ significantly from predictions (observed redshift = 0.0328 ± 0.001; predicted range: 0.078 - 0.096). This shows that directions, or speeds, or some combination of both, of the jets may be independently determined or affected by the environment. We are currently trying to understand the origin of this 'unruly' behavior of SS 433's jets.**
- **The flux of Fe XXVI from the Eastern jet increased in the long eclipse observation on average by 91.48% comparing to the short reference observation. The flux of Fe XXV increased by 63%, S XVI increased by 190.5%, Si XIV increased by 141.9% and Si III increased by 267.2% in the Eastern jet. This might suggests a changing intrinsic accretion flow during the observation. On the contrary, Fe, S, and Si lines from the Western jet were mostly blocked during the whole long eclipse observation.**

Reference and Acknowledgement

- Marshall, H. et al., 2013, ApJ, 775, 75.
- Marshall, H. et al., 2002, ApJ, 564, 941.
- Houck, J. C. & Denicola, L. A., 2000, ASPC, 216, 591.

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