

## Modeling the SS 433 Jet Bends

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We fit Chandra HETGS data obtained for the unusual X-ray binary SS 433. While line strengths and continuum levels hardly change, the jet Doppler shifts show aperiodic variations that probably result from shocks in interactions with the local environment. The X-ray and optical emission line regions are found to be related but not coincident as the optical line emission persists for days while the X-ray emission lines fade in less than 5000 s. The X-ray spectrum of the blue-shifted jet shows over two dozen emission lines from plasma at a variety of temperatures. The emission measure distribution derived from the spectrum can be used to test jet cooling models.

*Keywords:* X-ray; binary

### 1. Introduction

SS 433 is a very unusual binary system that has been the subject of many studies. It is well known for its optical spectra, which show Doppler shifted emission lines that periodically vary. These periodic variations are well-modeled as originating in twin, oppositely directed jets with flow velocities of about  $0.26c$ , whose orientations sweep out cones with a half-angle of about  $20^\circ$  due to “slaving” of the accretion disk orientation to the companion star’s precession. In addition, there is a periodic torque exerted by the companion that can cause the disk to nutate slightly. See reviews by Margon<sup>1</sup> or Fabrika<sup>2</sup> for observational details of SS 433 and for discussions of physical models.

### 2. Previous Observations

The X-ray spectrum of the jet shows emission lines<sup>3</sup> that are well modeled as thermal emission from an expanding, cooling plasma.<sup>4</sup> Previous observations using the *Chandra* High Energy Transmission Grating Spectrometer (HETGS<sup>5</sup>) usually show abundant

emission lines. Models based on thin, collisionally ionized plasmas at several temperatures are generally good fits to the data, making it possible to test models of the jets’ thermal evolution.

### 3. Observations

About 200 ks of *Chandra* observations were obtained in August, 2005 in order to detect weaker emission lines and to track variations in the line Doppler shifts. Simultaneous optical spectroscopy (by TCH) and VLBA (by AJM) were obtained in order to model the relationship between the various emission regions. Some preliminary results were reported earlier,<sup>6,7</sup> calling attention to a Doppler shift change over a 20 ks interval, much shorter than the nutational, orbital or precession periods of 6.29, 13.08 and 162.15 days, respectively.

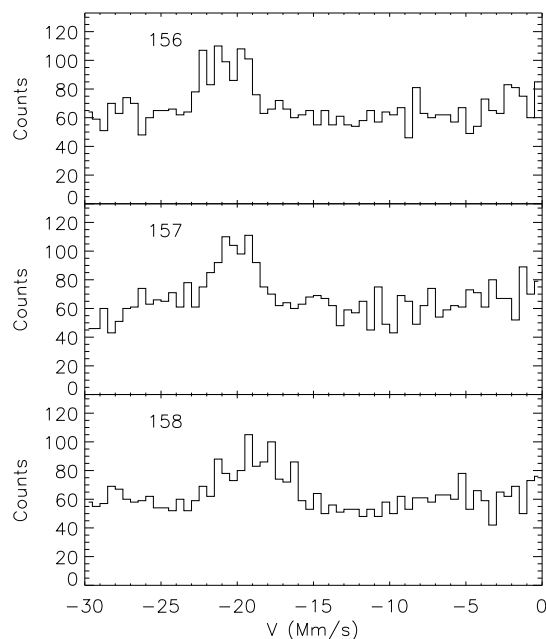


Fig. 1. Consecutive 5 ks portions of the blue jet emission line movie.

#### 4. Analysis

Fig. 1 shows three consecutive frames of a movie constructed from the *Chandra* HETGS data.<sup>a</sup> Each frame represents a velocity profile in a 5 ks time slice. For specific, strong emission lines with rest energies  $E_0$ , the X-ray events from an energy range  $[E_0, 1.1E_0]$  were accumulated in 500 km/s bins to produce a velocity profile every 5 ks. The Ly $\alpha$  lines of Mg XII, Si XIV, and Fe XXVI were chosen and combined in the rest frame, along with the He-like line, Fe XXV. The three frames shown in Fig. 1 were chosen from the time period where the Doppler shift of the blue jet was most rapidly changing. The average Doppler shifts in these three frames are -0.0694, -0.0687, and -0.0647, with uncertainties of  $\pm 0.0007$ .

#### 5. Discussion

We combine many spectra outside of eclipse and correct them for the changing blue-shift, shown in Fig 2. Also shown in Fig 2 are the Doppler shifts of the red jet as a function of time and the computed jet velocity ( $v_j$ ) and its angle to the line of sight, de-

termined every 5000 s from the red and blue jet Doppler shifts (assuming oppositely directed beams with identical jet speeds<sup>4</sup>). The source flux did not vary significantly over the course of the campaign, so the computed flux spectrum of the blue-shifted component from the eclipse observation almost exactly matches the average unocculted spectrum below 3 keV (Fig. 3). Most telling is that the blue jet lines in the composite spectrum match to better than 10% those of the eclipse spectrum. Thus, it appears that the jets have not changed physically over the course of the campaign, spanning about 10 days and that the blue-shifted jet's cooler portions are fully visible during the eclipse. The residuals at energies just below the Fe XXV line are mostly due to red-shifted Fe XXV lines that do not subtract out in this method of analysis because the method is only correcting for the Doppler shift of the blue-shifted jet lines.

Most of the blue Fe XXV and Fe XXVI jet lines also appear to subtract out rather cleanly in this method of comparing the spectra. At most, 20% of the jet that provides the blue jet's Fe XXV line is blocked. Up to 50% of the blue jet's Fe XXVI could be blocked as well. If part of the blue jet is blocked, it seems to be only the hottest part of the visible part, requiring that the companion star be somewhat larger than indicated by earlier data.<sup>8</sup> It is somewhat harder to determine how much of the red jet is blocked because it was somewhat fainter than the blue jet during this campaign, when there was a large difference in the blue and red Doppler shifts.

#### 6. Conclusions

The Doppler shifts of the blue jet lines were observed to undergo a rapid change during the 2005 August campaign with the *Chandra* High Energy Transmission Grating Spectrometer. These changes occurred over a much shorter time scale than any of the known periodicities in the system due to precession, orbit, or nutation and are not observed at the same time in the red-shifted jet. Because the cooling time of the X-ray emitting gas is  $\sim 1$  s,<sup>8</sup> the change must be due to a local effect within  $10^{10}$  cm of the point where the jet is formed or redirected. Redirection was suggested by Begelman, King, and Pringle<sup>9</sup> as a way to tie the initial jet direction to the black hole spin direction and the normal to the orbital plane. In their model, the jets align with winds from the outer parts of the accretion disk that are precessing about the black

<sup>a</sup>The original movie is available at <http://csr-dyn-135.mit.edu/~hermann/ss433/index.html>.

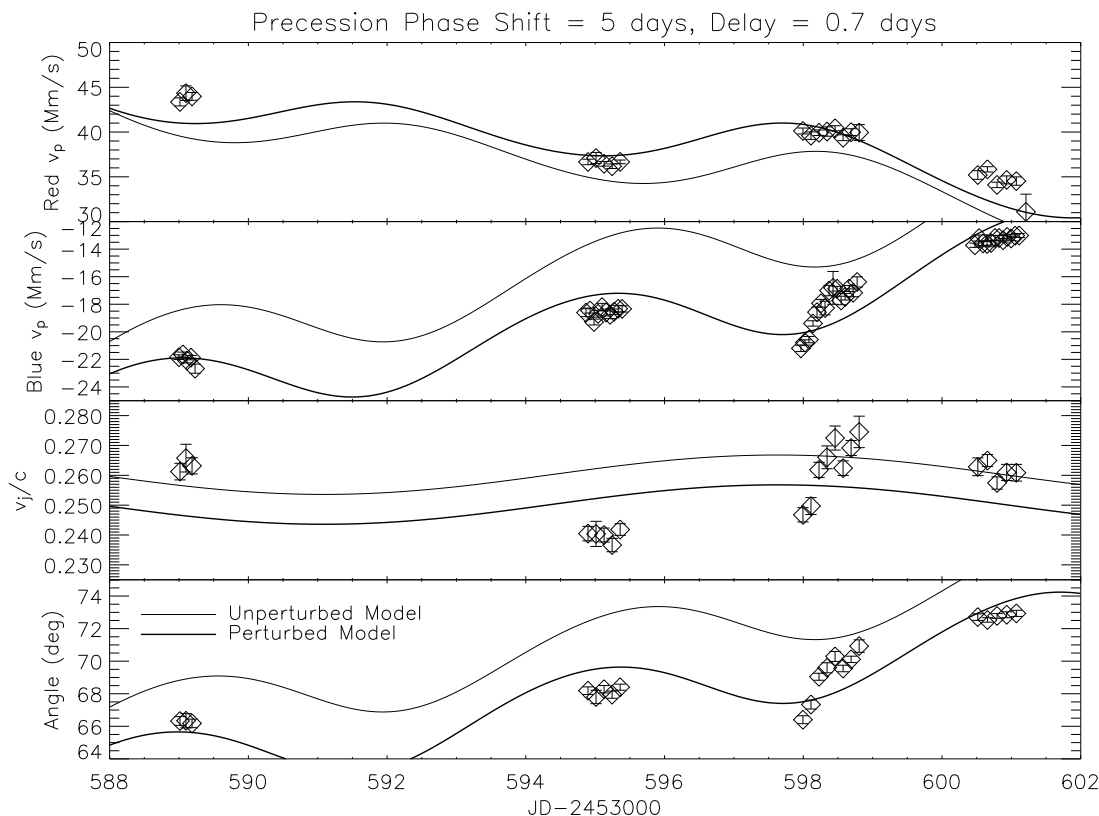


Fig. 2. Doppler shifts for the red and blue lines and derived quantities. From the top, the panels show the Doppler shift of the red jet, the Doppler shifts of the blue jet, the inferred jet velocity relative to  $c$ , and the inferred angle to the line of sight. The angle and  $v_j$  are computed under the assumption that the blue and red jets are directly opposed with the same speed. The correlation of the residuals on JD 2453598 appear to result from a breakdown in these assumptions, rather than true velocity and jet angle correlations because the Doppler shift of the red jet doesn't vary on that day.

hole spin direction. In this model, the thermal gas giving rise to X-ray emission lines must be very close to the point at which the jet is redirected, perhaps from shocks at the wind-jet interaction point.

Furthermore, the source properties were remarkably steady during the campaign, so that it is straightforward to compare the spectrum during eclipse to other periods during the orbit. It is clear that the cool portions of the X-ray emitting jet are not occulted during the eclipse but it does appear that the hottest part of the blue jet is partially blocked. This observation alone leads us to the conclusion that the star is larger than previously estimated,<sup>8</sup> large enough to block the central source during mid-eclipse. For binary mass values reported by Hilwig & Gies,<sup>10</sup> part of the blue-shifted jet is blocked.

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## References

1. B. Margon, *ARA&A*, **22**, 507 (1984).
2. S. Fabrika, *Astrophysics and Space Physics Reviews* **12**, 1 (2004).
3. T. Kotani, N. Kawai, M. Matsuoka and W. Brinkmann, *PASJ*, **48**, 619(August 1996).
4. H. L. Marshall, C. R. Canizares and N. S. Schulz, *ApJ*, **564**, 941(January 2002).
5. C. R. Canizares, J. E. Davis, D. Dewey, K. A. Flana-

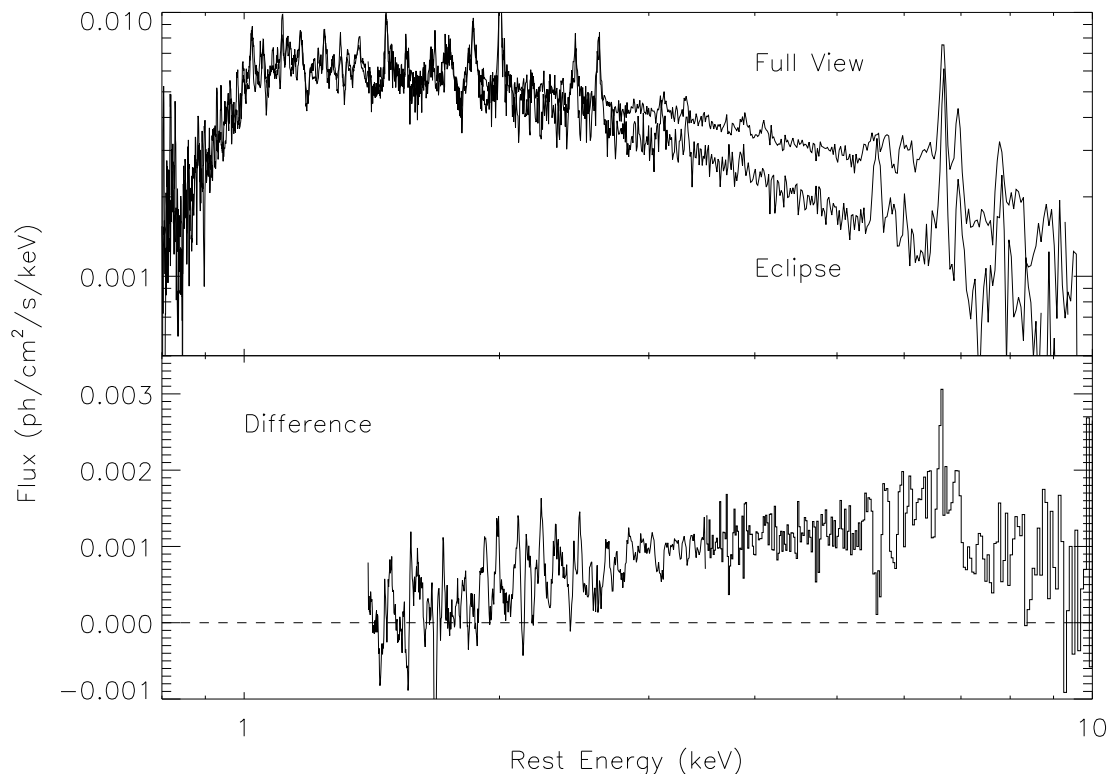


Fig. 3. Chandra HETGS spectra of SS 433 from just the medium energy grating data. *Top panel* Spectra outside of eclipse (top) and during eclipse (bottom). *Bottom panel* Difference between spectra in the top panel, giving a spectrum of the eclipsed emission region. Note that the continuum below 2 keV and all lines below 3 keV in the blue-jet spectrum are cancelled in the subtraction. The two spectra in the top panel were corrected for the blue jet's Doppler shift over several observations, so some of the red jet's lines show up in the difference spectrum. A prominent example is the Fe XXV line, which shows up in the 5-6 keV range in the difference spectrum.

- gan, E. B. Galton, D. P. Huenemoerder, K. Ishibashi, T. H. Markert, H. L. Marshall, M. McGuirk, M. L. Schattensburg, N. S. Schulz, H. I. Smith and M. Wise, *PASP*, **117**, 1144(October 2005).
6. H. Marshall, The SS433 Jets: Fraternal or Identical Twins?, in *High Resolution X-ray Spectroscopy: towards XEUS and Con-X*, (2006).
  7. H. L. Marshall, C. R. Canizares, S. Heinz, T. C. Hillwig, A. J. Mioduszewski and N. S. Schulz, Modeling the Relativistic Jets in SS 433 Using Chandra X-ray Spectroscopy, in *Relativistic Astrophysics Legacy and Cosmology - Einstein's Legacy*, eds. B. Aschenbach, V. Burwitz, G. Hasinger and B. Leibundgut (2008).
  8. L. A. Lopez, H. L. Marshall, C. R. Canizares, N. S. Schulz and J. F. Kane, *ApJ*, **650**, 338(October 2006).
  9. M. C. Begelman, A. R. King and J. E. Pringle, *MNRAS*, **370**, 399(July 2006).
  10. T. C. Hillwig and D. R. Gies, *ApJ*, **676**, L37(March 2008).