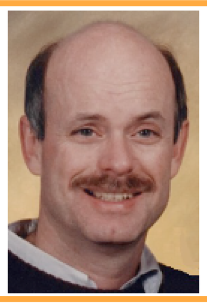

Aperiodic Variations of the SS 433 Jet Speed and Direction

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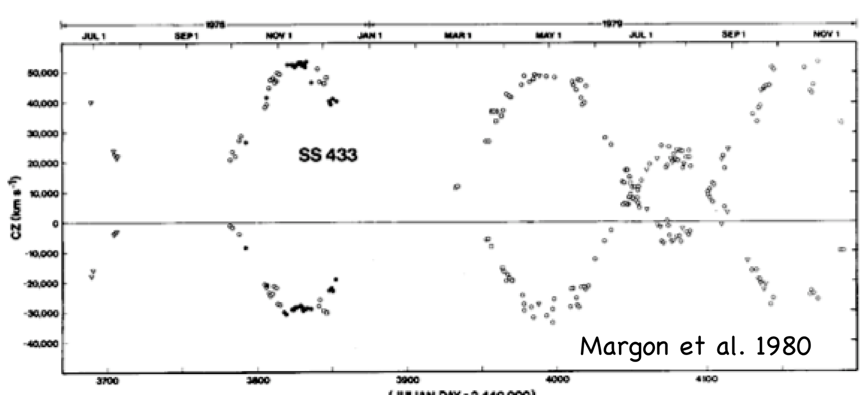
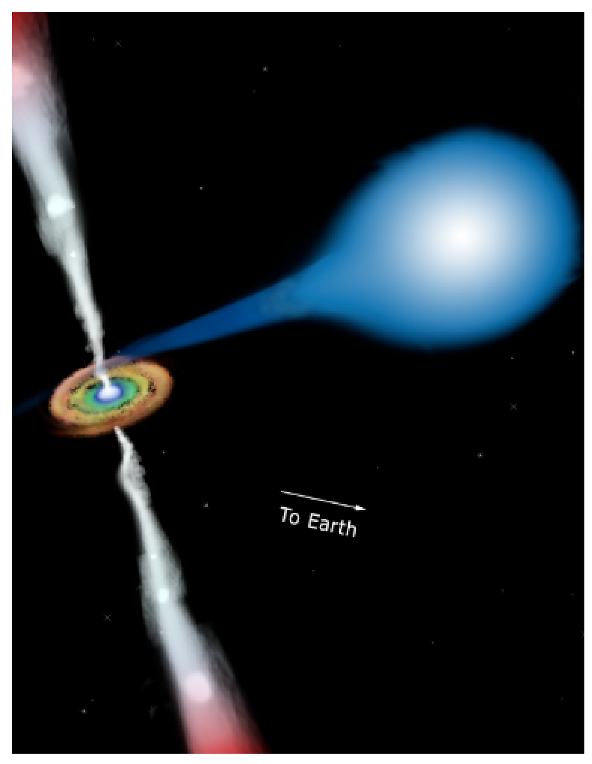
In August, 2005, we observed SS 433 using the High Energy Transmission Grating Spectrometer (HETGS) on the *Chandra* X-ray Observatory. The spectra and Doppler variations are shown.

SS 433 Background

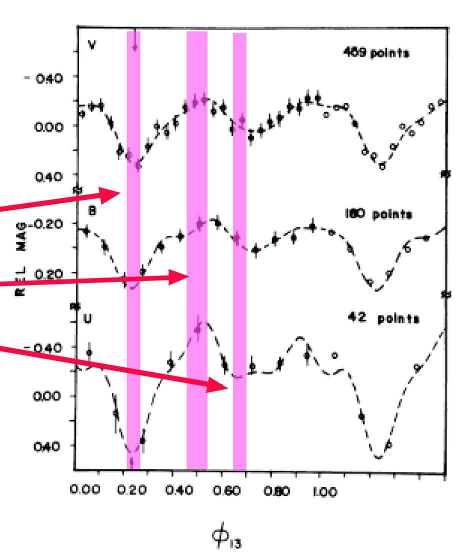
- Periodically Doppler shifting Hα, HeI and Hβ lines (see below)
- Model: oppositely directed jets at 0.26 c (see artist's impression at right)
- Precession period: 162 days
- Orbital period: 13.08 days
- Radio: verifies model and sets orientation
- Only jet known to contain baryons

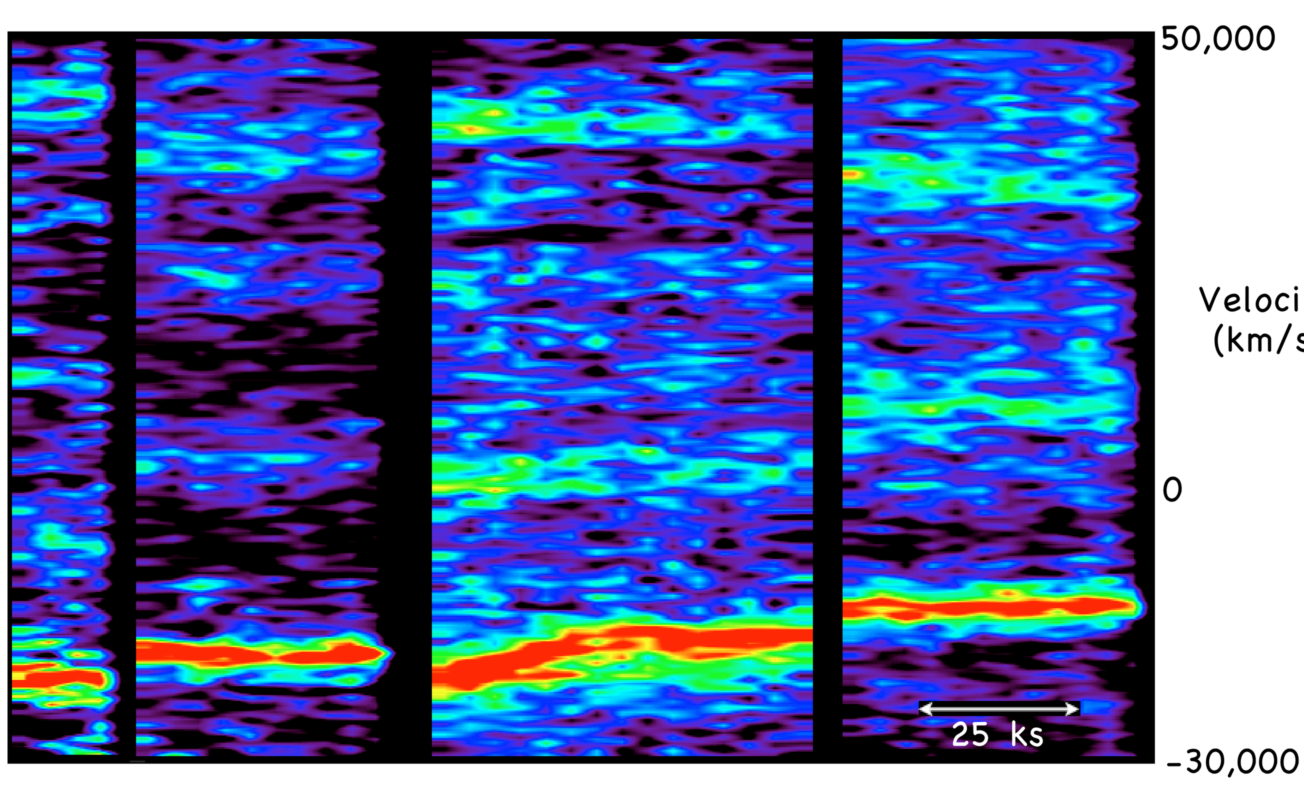




New Observations

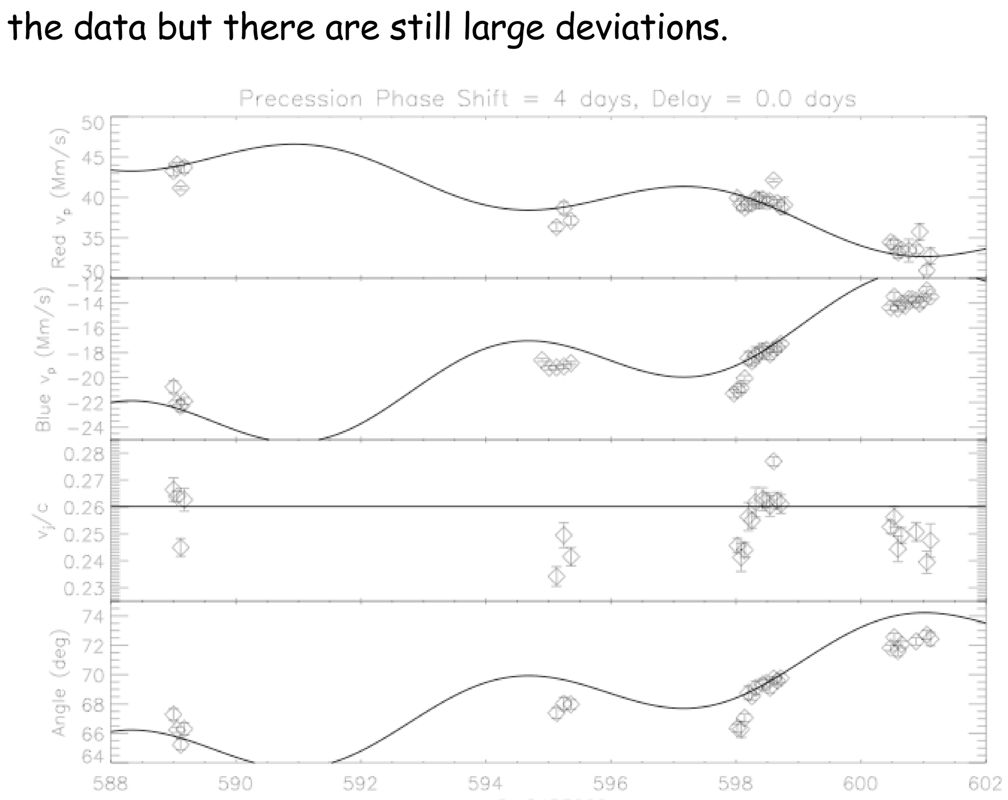
- 200 ks HETGS over 2 week span (PI: Canizares)
  "Trigger" ensured bright lines
  Aug. 12: 50 ks during eclipse
  Aug. 15-18: 120 ks non-eclipse
- Simultaneous observations
  optical spectroscopy (Hillwig)
  VLA, VLBA imaging (Mioduszewski, Rupen)
  RXTE (Marshall)





Top: Dynamic X-ray spectra, shifted to overlay emission lines of different elements. During the 3rd observation, the blue jet Doppler shift changed markedly over 20 ks.

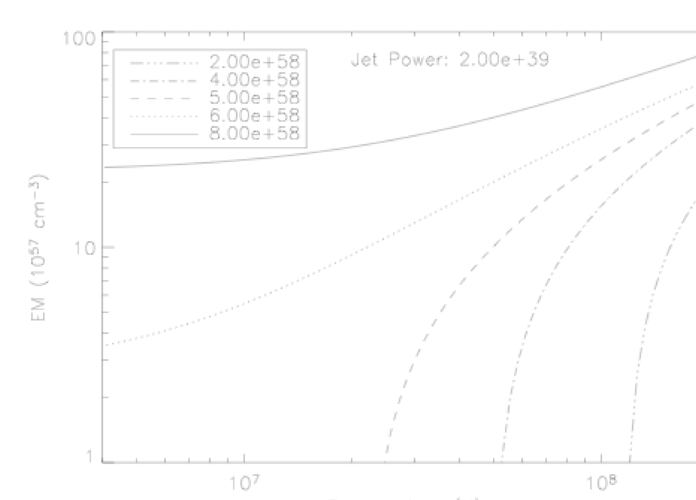
Bottom: Doppler shifts of the blue and red jets and computations of the jet speed and direction. The precession model was shifted by 4 days to provide a decent match to the data but there are still large deviations.



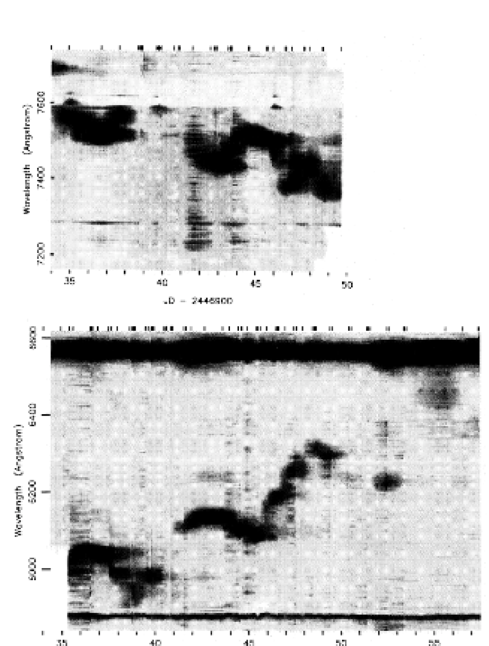
Jet Physics from X-ray Emission Lines

(most determinations from Marshall et al. 2002)

- Line Doppler shifts are consistent
  - Acceleration zone is not observed
  - All ions accelerated to same speed
- Line widths are all the same and narrow
  - Emission is not in nozzle or flaring zone
  - Jet opening angle is constant at 0.5°
  - Jet is not hollow — baryonic matter fills it
- Line strengths
  - Jet contains collisionally heated plasma
  - kT = 15-25 keV at jet base
  - EM(T), test cooling models
  - with continuum, get abundances
- Si XIII triplet
  - $n_e \sim 10^{14}$ cm^{-3}
  - n_e and EM give jet size ~ 10^{11} cm (for unit filling factor)
- Eclipse Observation (Lopez et al. 2006, in press)
  - Red jet X-ray emission lines were weak
  - Computed length of visible jet
  - Estimated size of companion star
  - Concluded: mass of black hole is about 20 ± 5 Msun

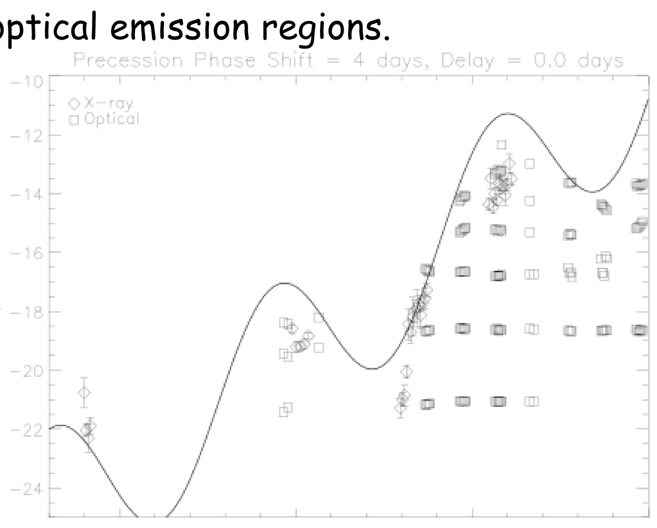


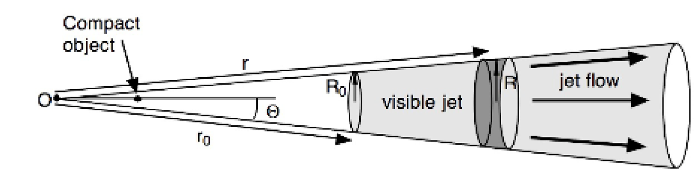
Above: Emission measure (EM) distributions predicted using a simple radiative cooling model. As the base EM drops to 2e58 cm-3, the EM at low temperatures drops dramatically, possibly explaining how low energy lines may be weak or absent on occasion.



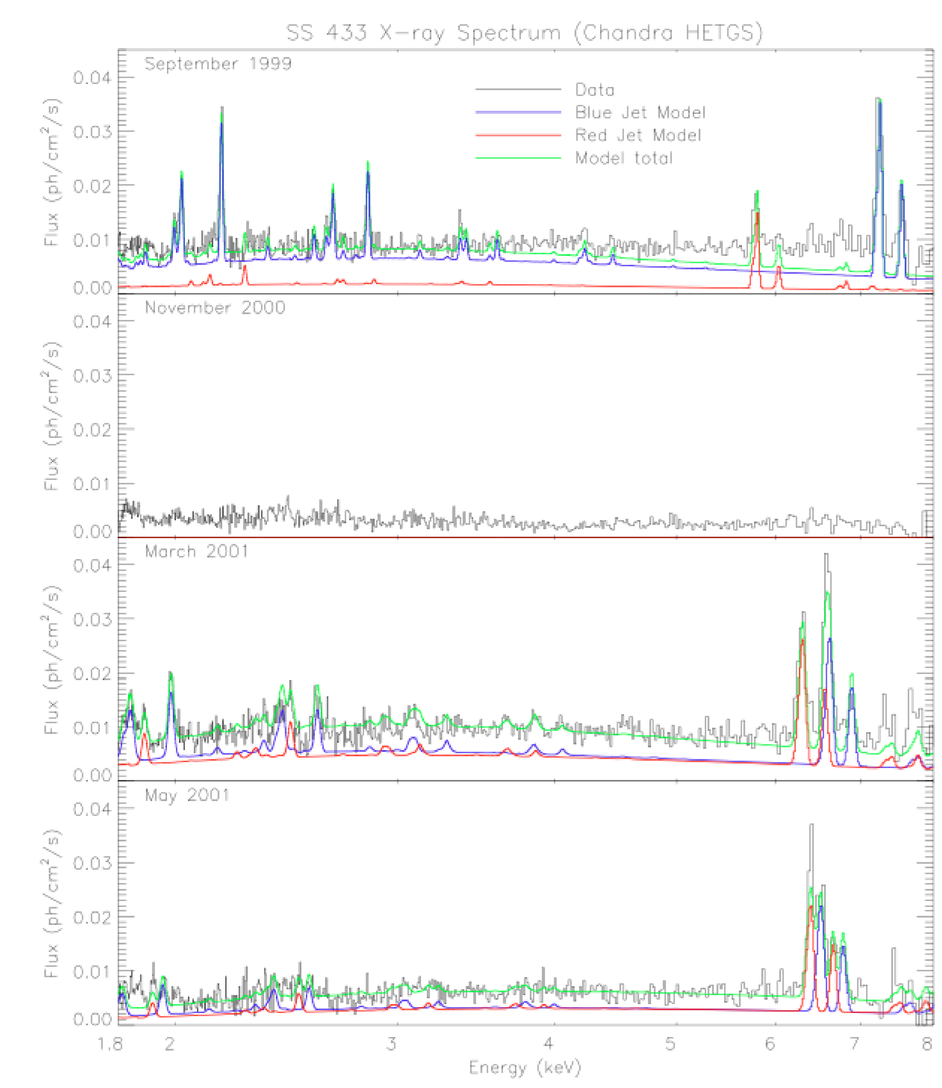
Above: Dynamic optical spectra of the Hα region. Sometimes lines at different shifts are found and persist for many days (Vermeulen et al. 1993).

Below: same data as to left but each optical line peak is shown, making it hard to relate the X-ray and optical emission regions.

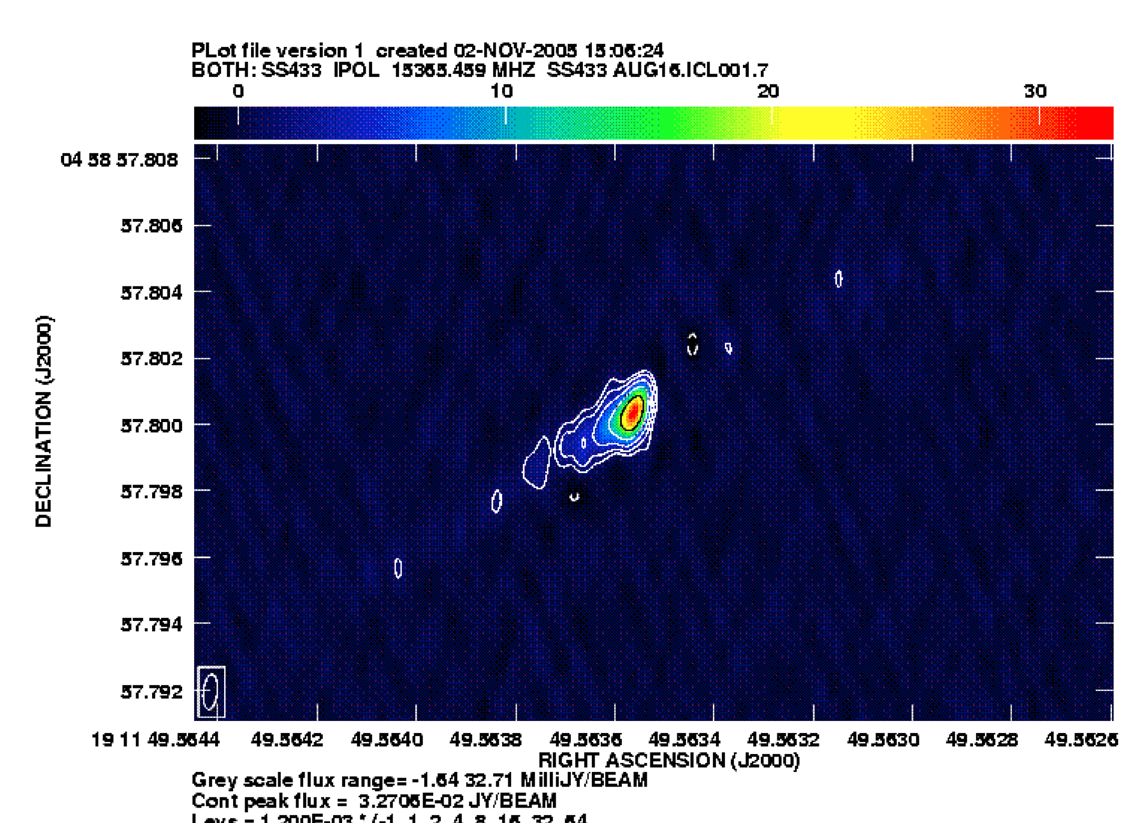




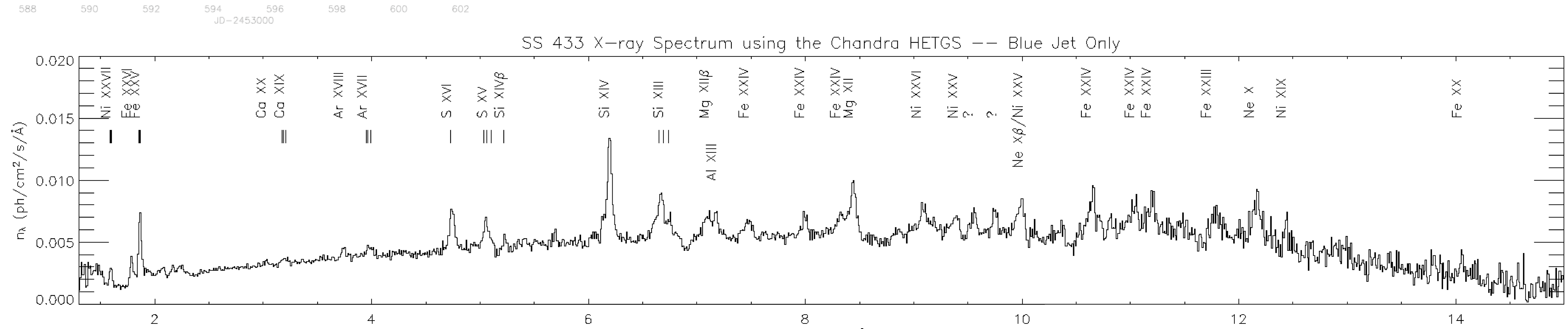
Jet geometry from Marshall et al. 2002



Above: X-ray spectra of SS 433 using the Chandra HETGS. (Top: also Marshall et al. 2002; middle pair: Lopez et al. 2006; bottom: Namiki et al. 2003). Models are the same as presented by Marshall et al. but Doppler shifted and multiplied by a smooth function of energy. The Fe XXV and XXVI lines are prominent during eclipse (Lopez et al. 2006). All lines seem to be absent in the November 2000 observation.



Above: Simultaneous VLBA data from one point in the observations. The red-shifted jet (to west) is much weaker than the blue-shifted jet than expected from Doppler boosting, suggesting intrinsic variations.



Above: X-ray spectra from all 200 ks of the new observations, after correcting for Doppler shifts. Weak lines are readily detected.

This work was supported in part under Smithsonian Astrophysical Observatory (SAO) contract SVI-73016 for the Chandra X-Ray Center (CXC).