The Chandra Legacy Project of HETG zeta Pup Observations: Variability

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The Chandra legacy project to obtain an extremely deep, high resolution gratings X-ray spectrum of the nearby early O star zeta Pup is now complete. A total of 821 ks of exposure time has been accumulated within a ~1 year time frame with the HETGS gratings system and the ACIS detector on Chandra, yielding X-ray spectra 2-20 A with a resolution of 0.023 A (meg) and 0.012 A (heg). Here we describe several of our techniques that are used to search for variability in the dataset.

Time-resolved X-ray Spectra

For the purpose of studying variability in the emission lines of zeta Pup, we divided the observations into contiguous time slices, each approximately 9 ks in exposure time.

21 Obsids of zeta Pup

9 ks time slices, each a fully calibrated spectrum

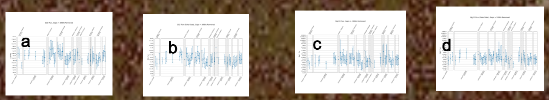

Figure 1: S XV, real (a) and fake (b) data flux determined from gaussian fit of each double-slice region, including the 1 sigma confidence limits. Periods of time with no observations have been removed from the plot. Mg XII real (c) and fake (d) data fluxes are also shown.

The time slices were created from Level 1 event files obtained from the Chandra archive, using the TGCat software (Huenemoerder et al. 2011). Standard calibrations were produced separately. Several techniques were used for analysis, including moments, Also, flux measurements and centroids are based on gaussian fits to the data for 18 ks time slices, obtained with a running window through the original 9 ks time slices. Each 18 ks time slice is by definition quite noisy, so we are only interested in trends. To verify the results, a series of fake data time slices were created with a constant emission profile and the random application of Poisson noise.

The mean, st dev, median, and range were compared between the real and fake data for S XV, Si XIV, Si XIII, Mg XII, Mg XI, and Ne 10. The st dev and range were always larger for the real data than the fake data, which can be an indication of variability. But in most cases the real data values were within the 1 sigma errors of the fake data, as can be seen in Figure 1.

Caveats
- Gaussian profile is probably not the best model for the data; best we can do with the time slices
- **There is an indication that some of the triplet profiles have underlying broad emission and/or line profiles with broad tails. This is not included in the fits.**
- **The S XV may have satellite lines of S; these are not presently included in fits**
- Width of the r, i, **and f lines were constrained, but these lines sometimes bumped up against the constraints during the fits.**

Comparison to XMM data

We compared the broad band fluxes of grating data obtained in 2018-2019 to those derived from previous XMM observations. While our Chandra campaign covers 1yr in time, XMM observed zeta Pup once a year for calibration purposes, so there are more observations but not close together in time.

As in Naze et al. 2018, we used two indices :
* VI = variability index = (mas-min)/(max+min), yielding an idea of the relative amplitudes of the changes
* F_var in %= the fractional variability (from Edelson et al. 2002) giving an idea of the variations above the noise :

Chandra results:
VI = 0.34+-0.16, 0.70+-0.25,0.25+-0.16 in 0.6-4, 0.6-1.2, 1.2-4 keV bands
F_var in %= 4.9+-0.5, 10.2+-0.8, 3.7+-0.6 in 0.6-4, 0.6-1.2, 1.2-4 keV bands
XMM results:
VI= 0.099+-0.007 and 0.095+-0.013 for 0.6-1.2, 1.2-4. keV bands
F_var in % = 4.0+-0.2 and 2.7+-0.2 for 0.6-1.2, 1.2-4. keV bands

-> The Chandra dataset shows more variability than the XMM dataset.

S XV Flux Variability

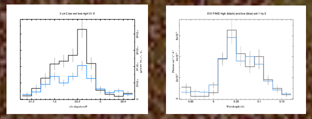

Figure 2: Left: Profiles of S XV emission lines for two sets of time slices selected on the basis of the highest and lowest flux parameters in S XV. Rght: Same as plot on the left, except using fake data.

Two groups of time slices were selected that showed high count rates and low count rates, respectively. The profiles of these 2 groups (100 ks exposure for each group) were compared for the He-like S XV triplet (Figure 2). A clear difference in flux levels is apparent, beyond the error bars:approximately 50% flux in the low group vs, the high group. A similar comparison with fake data did not reveal this flux difference.

The variability in the S XV line fluxes is an important new finding because the S XV line is believed to be formed close to the stellar surface, at the base of the wind. The changes seen (coupled with possible changes in the underlying temperature-sensitive SXIV DR lines), must indicate a short-term (< 1d) change in the local X-ray-producing environment near stellar surface.

Conclusions

***The Chandra dataset appears even more variable than XMM multiyear dataset for a broad bandpass**
*** Flux changes in the S XV lines (and/or DR lines) indicate a rapidly changing local environment for X-ray production close to the stellar surface, which will constrain wind models**
*** Period searches and individual emission line variability studies are in progress**

Huenemoerder, D. P., Mitschang, A., Dewey, D., et al. 2011, AJ, 141, 129
Naze', Y., Ramiaramanantsoa, T., Stevens, I. R., Howarth, I. D., & Moffat, A. F. J. 2018, A&A, 609, A81
Edelsen, et al., 2002, ApJ,,568,610.

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