HST FUV/NUV Photometry of the Putative Binary Companion to the SN 1993J Progenitor

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1 Introduction

Type IIb supernovae (SNe IIb) are a subclass of core-collapse SNe which exhibit hydrogen lines typical of all SNe II in the early stages, while at later stages have He I lines typical of SNe Ib and lack the expected broad Hα emission of SNe II ([1]). The prevailing theory explaining SNe IIb requires the addition of a binary companion to the progenitor which strips the outer H envelope of the progentior prior to going supernova. The hydrogen emission from the reduced envelope is present in early times, but as the ejecta expands and cools the spectrum becomes dominated by emission from denser regions closer to the He core of the progenitor and thus begins to resembles SNe Ib.

The progenitor to SN 1993J, a SNe IIb, was identified in pre-explosion images and subsequent studies determined it was a K-type supergiant ([2], [3], and [4]). Using high resolution images taken with the ACS High-Resolution-Channel on HST coupled with high-resolution LIRIS-B/KECK spectrum, Maund et al. ([4]) detected absorption lines at the position of SN that were consistent with an early-type B supergiant which provided the first hints of a surviving companion.

Finally, Fox et al ([5], hereafter Fox 2014), used 2012 HST observations from COS and WFC3 to analyze SN 1993J almost 20 years post-explosion. By extracting photometric magnitudes from the WFC3 observations, they were able to derive stellar models for stars E – H and disentangle their flux contributions to SN 1993J spectrum. Using a template spectrum of SN 1993J from STIS observations taken in 2000, they modeled circumstellar interactions from the supernova. Comparing the models to the 2012 COS spectrum, which contained a blend of the flux from SN 1993J and stars E – I, they showed that there was a clear FUV excess that could not be readily explained by contributions from the neighboring stars. Instead, the addition of a hot B-star was required to accurately explain the apparent FUV excess.

2 Observations

- The F140LP bandpass has coverage from ~1340 to 2000 Å and will allow us to deblend flux contributions from SN1993J, the companion, and neighboring stars at the pivot wavelength of the filter, 1528 Å.
- This will allow a direct measurement of the FUV excess found by modeling the COS spectrum in Fox 2014.

Instrument	Filter	Exp. Time	Aperture	Dither	Date
ACS/SBC	F140LP	3150s	Full Frame	------	Apr. 4th, 2015
WFC3/UVIS	F218W	3000s	UVIS2-C512C-SUB	Box Dither	Mar. 27th, 2015
WFC3/UVIS	F275W	2260s	UVIS2-C512C-SUB	Box Dither	Mar. 27th, 2015
WFC3/UVIS	F336W	640s	UVIS2-C512C-SUB	Box Dither	Mar. 27th, 2015

Image Processing

- Process RAW data products using the pipeline reduction packages, CALACS and CALWFC3.
- For ACS/SBC, apply the distortion correction via AstroDrizzle to account for geometric distortion of SBC.
- For WFC3/UVIS, perform cosmic-ray rejection and combine the dithered data with AstroDrizzle resampling to a finer plate scale to improve the sampling of the PSF.

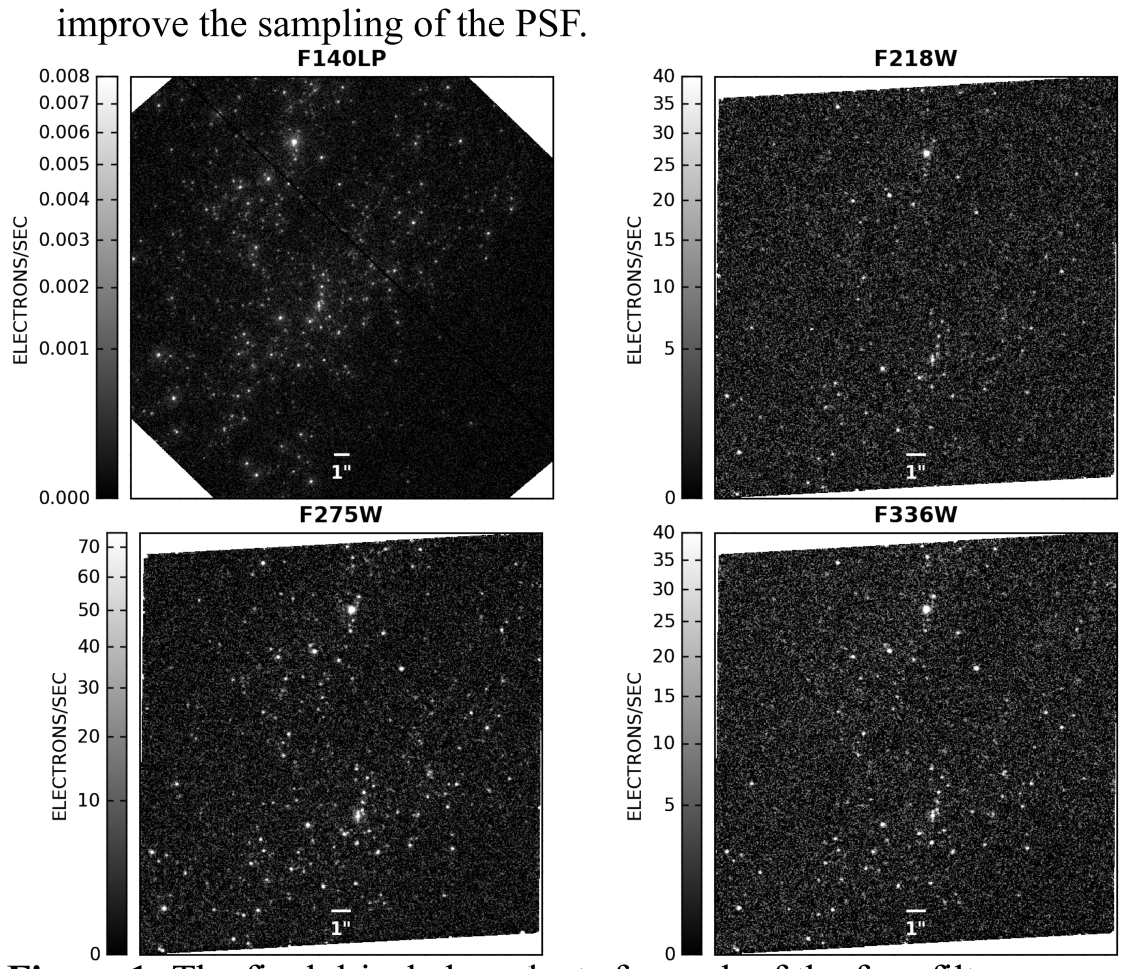


Figure 1: The final drizzled products for each of the four filters.

3 Data Analysis

For HST data, there are three ways for generating a PSF for photometry; model it with TinyTim ([6]), build if from effective PSF (ePSF) models ([7]), or build it using a photometry package (e.g. DAOphot, DOLHPOT). TinyTim was shown to overestimate flux of in the wings of ACS/SBC PSF by ~10% introducing unwanted systematics into the analysis ([8]). Next, ePSF's cores only exist for the F275W and F336W filters and so we cannot apply them to the F140LP or F218W data. Dolphot has support for WFC3/UVIS, but not ACS/SBC. For these reasons we chose to build the PSF using DAOphot.

Finding candidate PSF stars

For each observation, we use SExtractor ([9]) to identify all sources present in the image. We use an absolute threshold for detection and set the *DEBLEND_MINCONT*= 0 forcing the software to attempt deblending as if each detected source was composite. With sources found, we use the A*_IMAGE, B_IMAGE* parameters computed by SExtractor to apply an eccentricity cut to identify a subset of point-like sources. Next, we apply a flux cut to this subset keeping only those sources with sufficient S/N for use in PSF building process. This generates a list of candidate PSF stars for visual inspection. An example of this is shown in **Figure 2.**

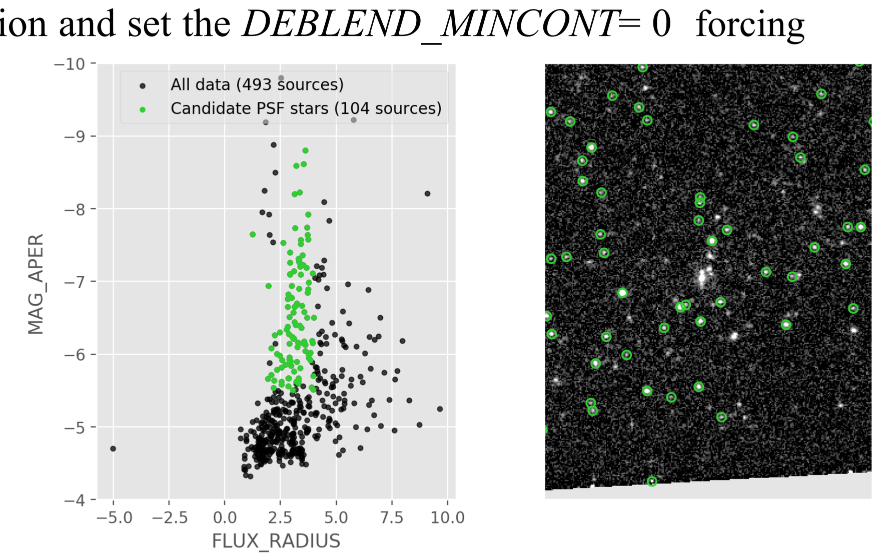
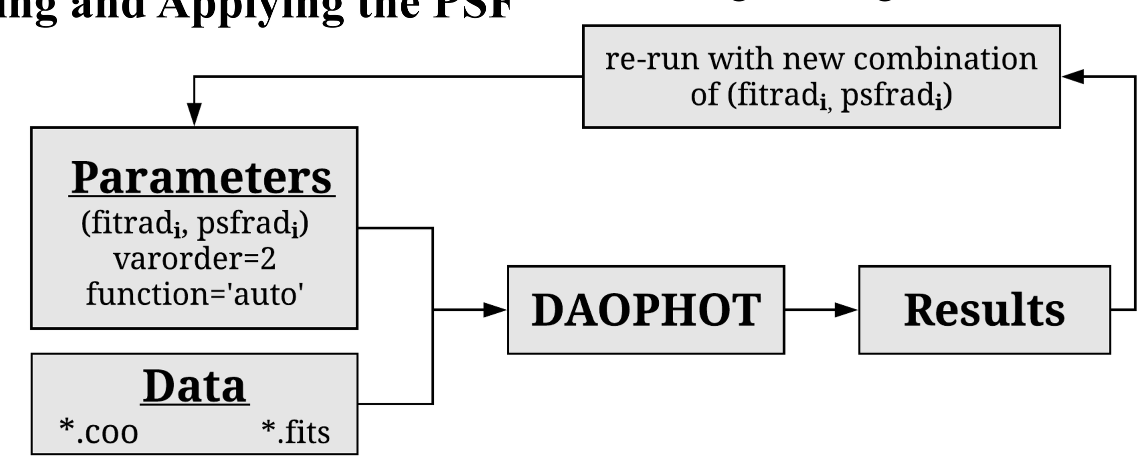


Figure 2: Left: All sources found by SExtractor are shown in black and all candidate PSF stars are shown in green. Right: The candidate PSF stars

Building and Applying the PSF



- Examine the residuals between the aperture and psf photometry for each combination of (fitrad$_i$, psfrad$_i$).
- PSF stars are all isolated with good S/N → $|m_{ap} - m_{psf}| \leq 0.05$ mag
- Using the combination that minimizes the residuals perform psf and aperture photometry on the entire field to derive the psf-to-aperture correction (**Figure 3**).
- Extract psf magnitudes of SN 1993J and the neighboring sources labeled in **Figure 4**.

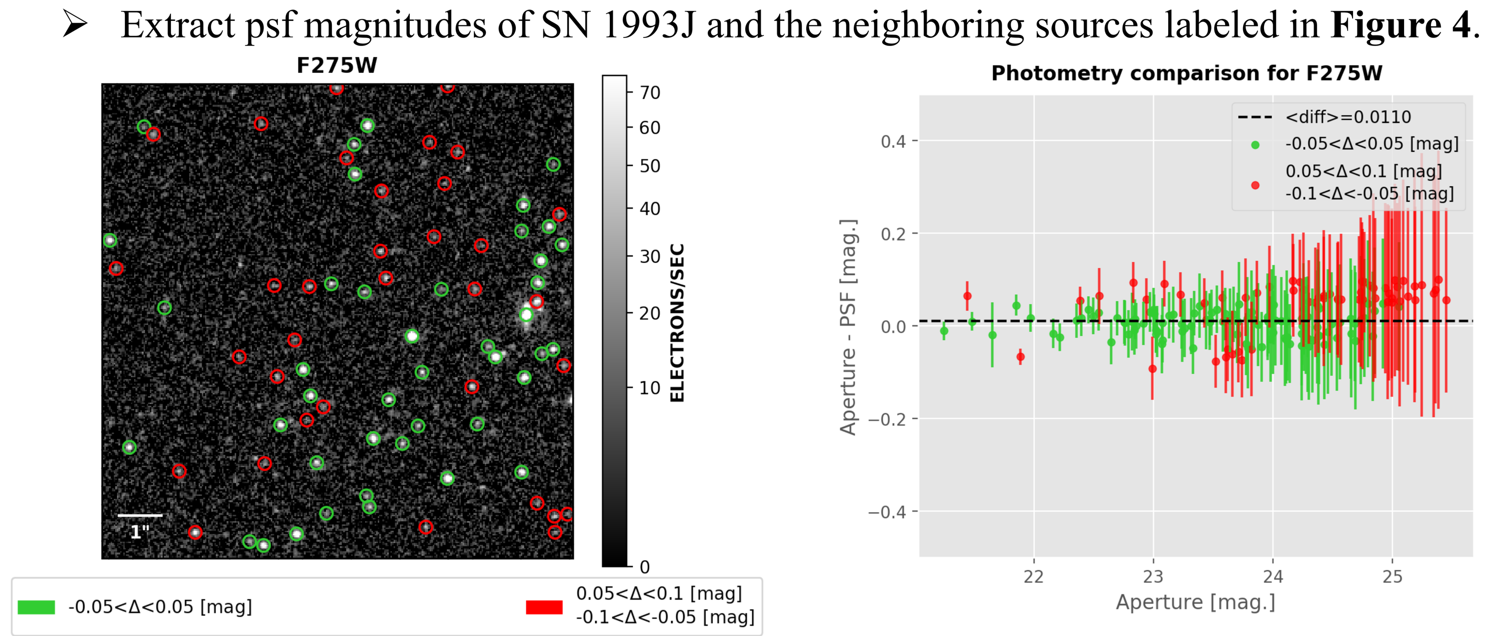


Figure 3: An example of the sources used to derive the psf-to-aperture correction for the F275W data. Green sources have residuals smaller 5%, while red have residuals between 5-10%. The correction (dashed horizontal line) is the average of the green datapoints.

4 FUV Excess

To measure the flux we performed neighbor-subtracted PSF photometry using DAOphot on all the observations. The PSF photometry allows us to disentangle the overlapping PSFs for stars E - I and SN 1993J+companion (**Figure 4**). This ensures that we only consider contributions from the sources within the PSF of the SN+companion when we compute the magnitude and subsequent flux for comparison with the SED of the putative companion. After the necessary aperture corrections have been applied, we perform the absolute flux calibration by computing the time-dependent VEGAMAG zeropoints with pysynphot ([7]) and applying them to our derived PSF magnitudes.

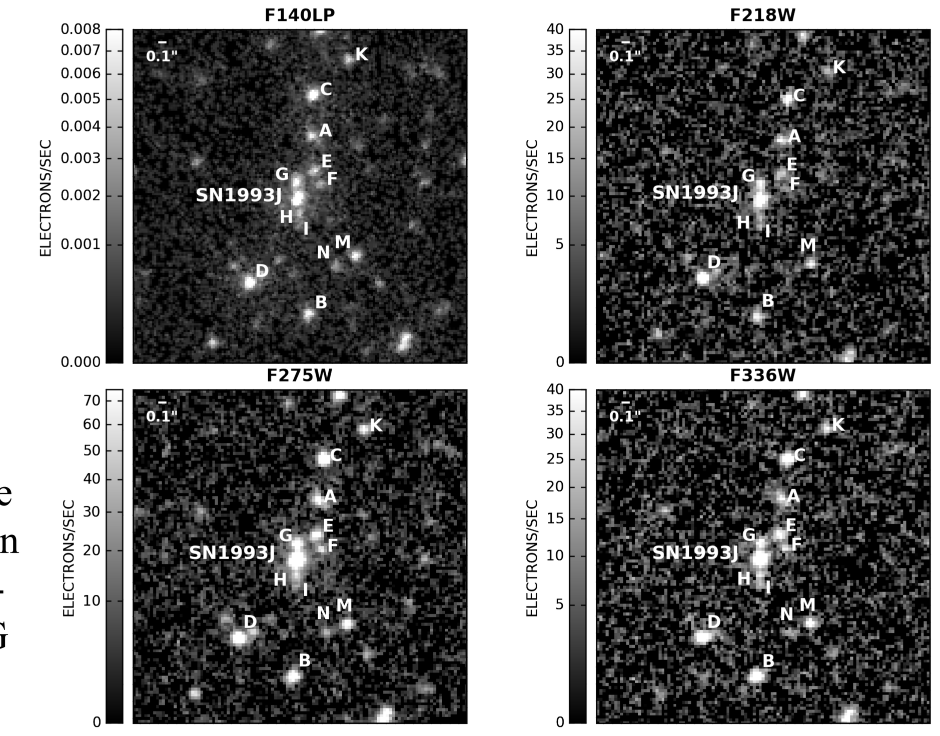


Figure 4: SN1993J and the previously identified sources in each of the four filters.

Following the work of Fox 2014, we perform the same analysis using the scaled STIS spectrum (**Figure 5**, blue line) from 2000 as the template for SN1993J. We use the previously determined scale factor from Fox et al to model the shock interactions from the expanding supernova with the circumstellar medium. This scale factor is anchored to the 2012 COS observations and so it serves as an upper limit of the SN contributions to the combined SN+companion spectrum as the SN has continued to expand and cool since 2012. We adopt the same stellar models for stars E - H derived in Fox et al using multi-wavelength WFC3 photometry (solid circles in **Figure 5**). We compare the FUV flux derived from the 2015 observations at 1528 Å (pivot wavelength of F140LP) with the predicted contributions from the companion star (**Figure 5**). We find that the flux of scaled STIS spectrum at the same wavelength is too low to explain the F140LP observations alone, and further that the flux obtained is consistent with what is expected from the putative companion.

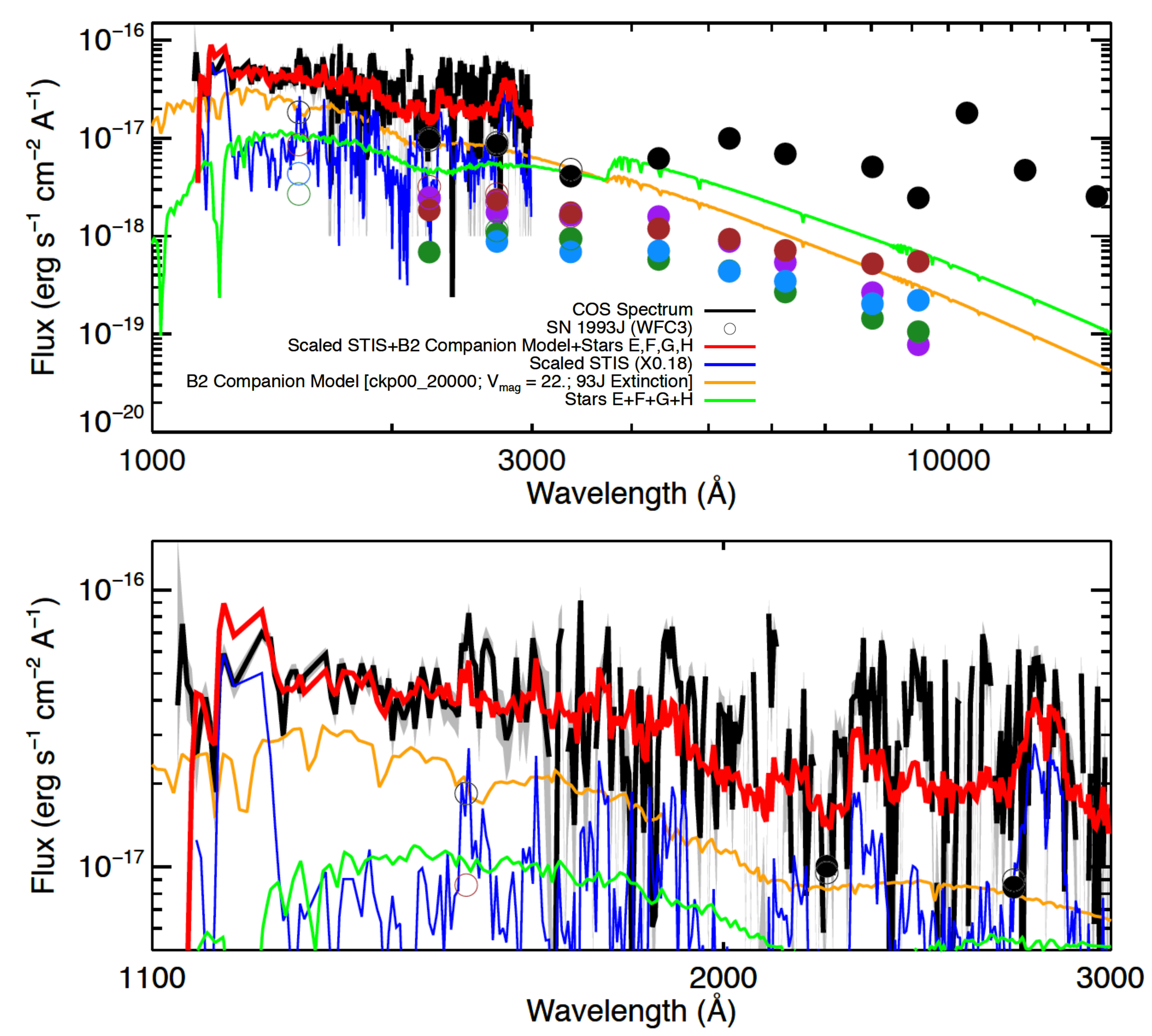


Figure 5: The top plot shows the consistency of the 2015 WFC3 fluxes (open circles) with the 2012 WFC3 fluxes (solid circles) in the common filters. It also shows the expected contributions from the SN (blue), the companion (orange), stars E – H (green) to the combined spectrum (red) and how well that matches the 2012 COS spectrum. The bottom is the same as the top, but zoomed in on the UV portion to highlight the consistency of the SBC photometry with the SED of the companion.

5 Conclusions

- The NUV photometry from the WFC3/UVIS data are consistent with the values reported in Fox 2014.
- The FUV photometry extracted from the ACS/SBC data is in good agreement with SED of the putative B2 companion. Assuming only two sources (within the PSF), this would be a direct detection of the companion.
- In the F140LP image there is a hint of a possible third source offset ~0.1" from the SN+companion (**Figure 4**). If this source truly exists, more work must be done to quantify its contributions to the excess.

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