The Expansion of 1E 0102.2-7219

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Introduction

1E 0102.2-7219 (hereafter E0102) was discovered in the *Einstein* survey (Seward & Mitchell 1981) of the Small Magellanic Cloud (SMC) and is the second brightest persistent source in the SMC after SMC X-1. E0102 is classified as an "O-rich" supernova remnant in the optical (Dopita et al. 1981) and is therefore believed to be the result of the core collapse of a massive star. Blair et al. 2000 estimate the mass of the progenitor to be ~25 M☉. It has a diameter of 0.75 arcminutes(13 pc) with a quite spherically symmetric morphology in X-rays (Gaetz et al. 2000, see Figure 1). The optical morphology is less symmetric and more complicated with bright filaments in [OIII] interior to the bright X-ray ring (Finkelstein et al. 2006). Vogt & Dopita 2010 have examined the 3D structure of the [OIII] filaments and conclude that the ejecta have an asymmetric bipolar structure that is indicative of asymmetries in the explosion. The X-ray luminosity is L_X(0.3-10.0 keV) =2.5x10^{37} ergs s^{-1} and the X-ray spectrum is dominated by H-like and He-like lines of O, Ne, & Mg (Rasmussen et al. 2000, Flanagan et al. 2004). Hughes et al. 2000 estimate the age to be ~1,000 yr while Finkelstein et al. 2006 estimate an age of ~2,050 yr based on proper motion measurements of 12 ejecta filaments with HST.

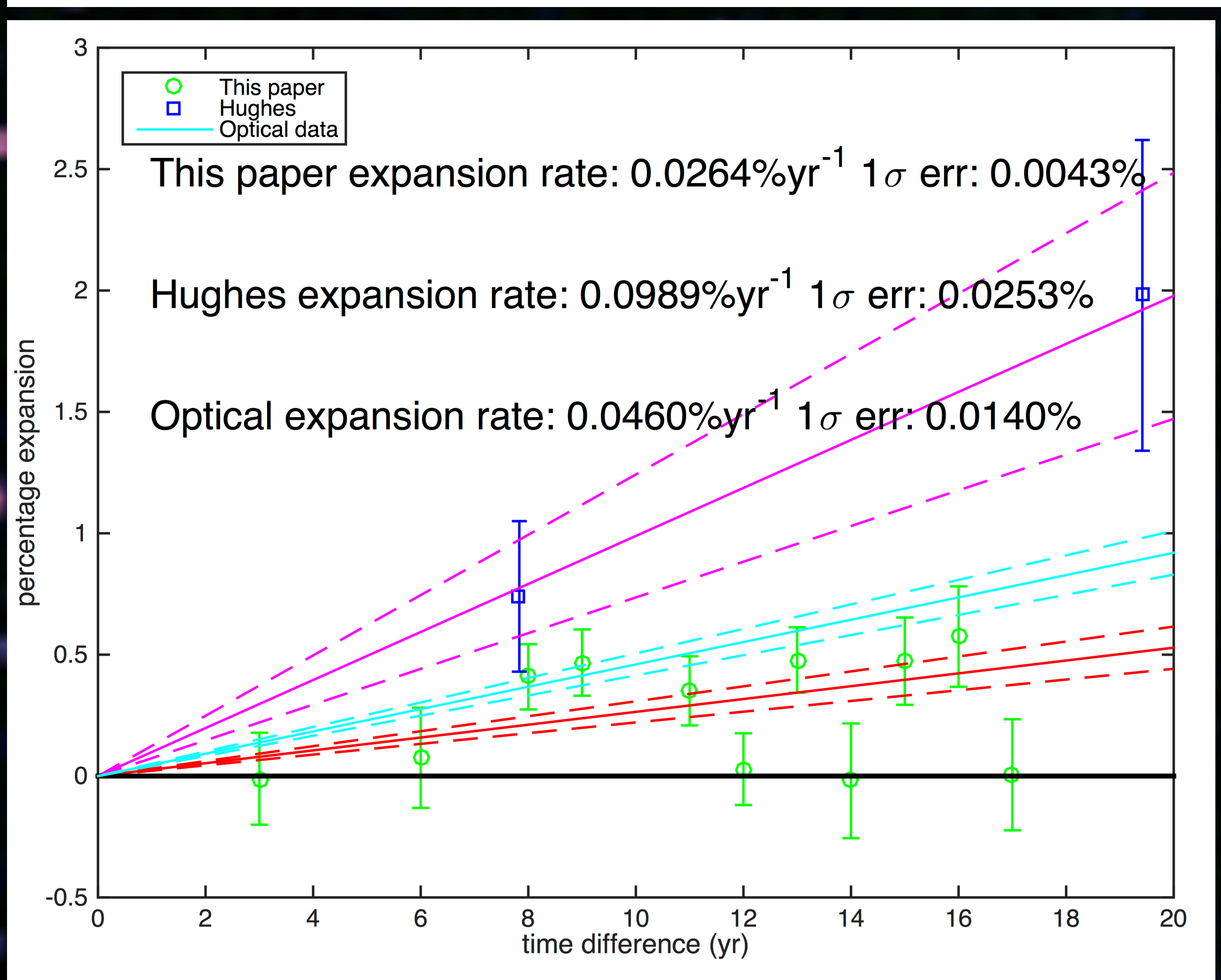
New Expansion Measurement

There are several complications with the Hughes et al. measurement of the expansion. First, they utilize data from three different telescopes and instruments, each with their own systematic uncertainties. *Chandra* has a 50% encircled energy radius of 0.4 arc seconds, while *ROSAT* and *Einstein* are closer to 4.0 arcseconds. Over the 19 year baseline, the outer blast wave would have moved 0.43 arc seconds if the expansion rate of 0.10 % yr^{-1} is correct. Second, they measure the global expansion of the remnant using all parts of the remnant and assuming the expansion is uniform both radially and azimuthally. The optical data show that the ejecta have a complicated structure in three dimensions (Vogt & Dopita 2010) and the X-ray bright ring has been modeled as two rings, one blue-shifted and one red-shifted, or as a cylinder (Flanagan et al. 2004). Finally, the early *Chandra* observation of E0102 suffered from significant pileup which depressed the observed count rate in the bright ring while preserving the true count rate of the fainter parts of the remnant.

We have adopted a simpler approach by analyzing only *Chandra* data and measuring the expansion of the outer blast wave. By restricting our analysis to only *Chandra* data, the data have the same telescope response for each observation but the *Advanced CCD Imaging Spectrometer* (ACIS) response is different for each observation. By restricting our analysis to the outer blast wave, we eliminate any complications with pileup, projection effects of the bright ring, or intensity variations as a function of time as the ionization timescale and temperature vary within the bright ring of ejecta. Our approach suffers from the complications that the outer blast wave is fainter and the observed counts decrease with time as the ACIS low energy response declines. In addition, all of the ACIS observations since 2006 have been executed in subarray mode such that there are usually no sources bright enough in a ~10 ks observation to use for registration. We have used the bright knot in the center of E0102 (shown in Figure 2) to register the images from different epochs under the assumption that this feature is blue-shifted with little or no velocity component in the plane of the sky similar to the optical filaments in the same region.

We constructed a model for the spatial distribution of E0102 using an early observation (OBSID 1423) and we then compare later observations to this model. Figure 1 shows the regions from which radial profiles were extracted. Figures 5 & 6 show sample radial profiles from OBSID 17380 for the directions angle=135 and angle=292.5. In each of these profiles a small shift to larger radii is indicated.

Figure 7: Measured Expansion rate compared to Hughes et al. 2000



Expansion Measurement

Hughes et al. 2000 compared one of the earliest *Chandra* images of E0102 to *ROSAT/HRI* and *Einstein/HRI* data to estimate the global expansion of the remnant. They measured an expansion rate of 0.100 +/- 0.025 % yr^{-1} which corresponds to a shock velocity of v_S~6,200 km s^{-1}. This velocity implies an electron temperature of 2.5 to 45 keV depending on the degree of collisionless electron heating. The electron temperatures measured from the X-ray spectra of the blastwave vary between 0.4-1.0 keV. They suggest that the apparent difference between these two estimates of the electron temperature can be reconciled if a significant fraction of the shock's energy is accelerating cosmic rays.

Figure 1: *Chandra/ACIS* image in the 0.35-8.0 keV band with the radial profile extraction regions indicated.

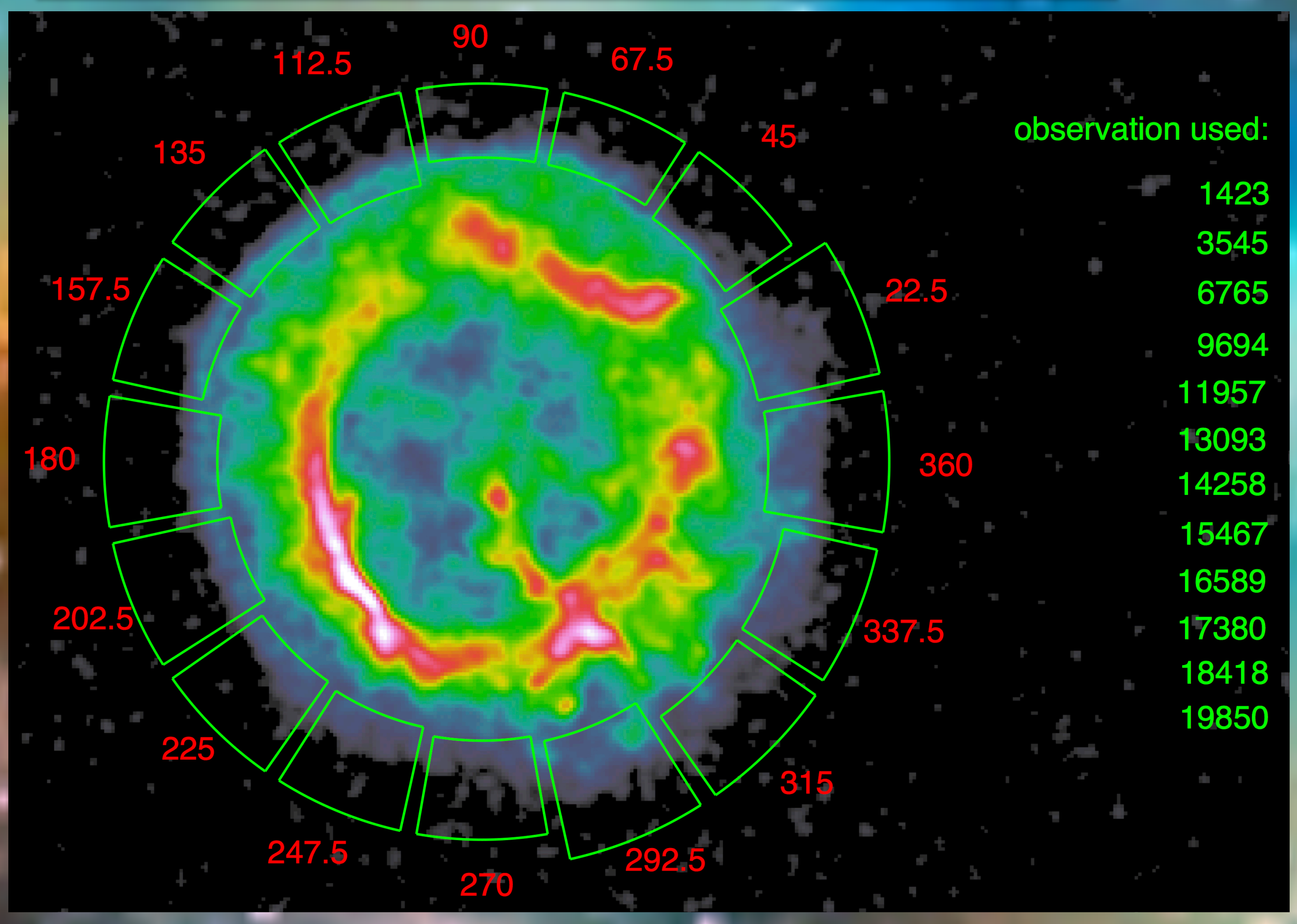


Figure 5: Radial Profile from OBSID 17380 for angle=135.

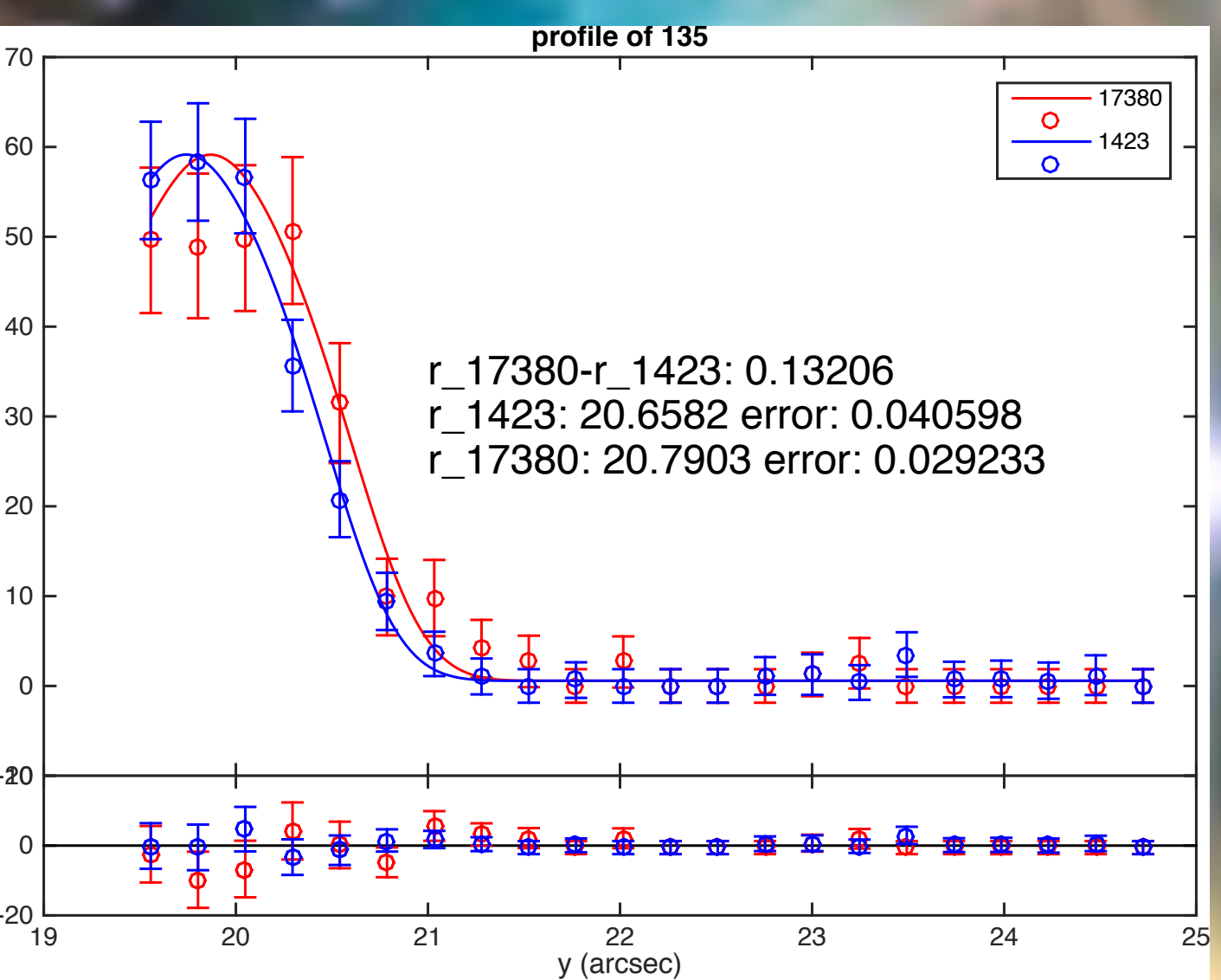
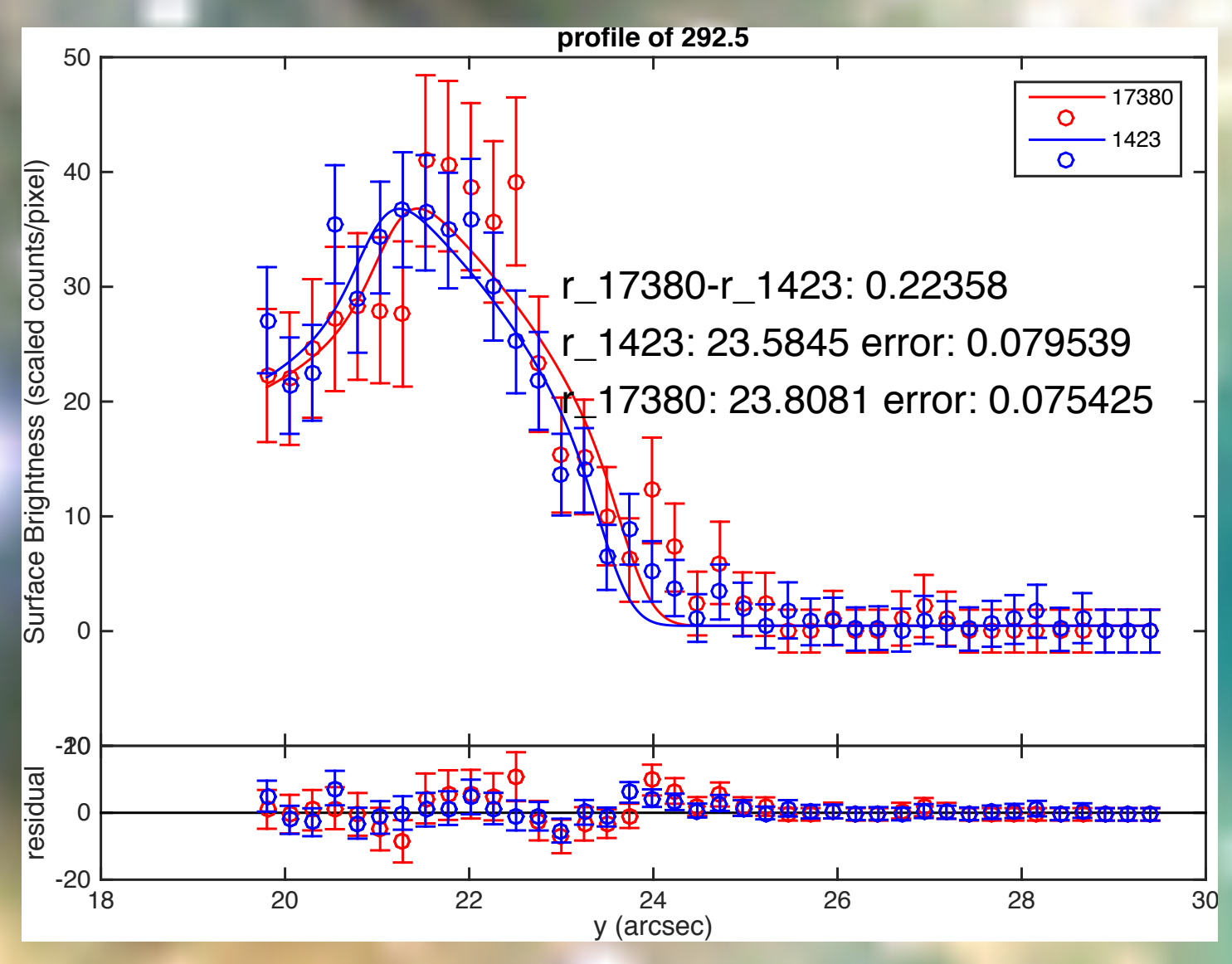


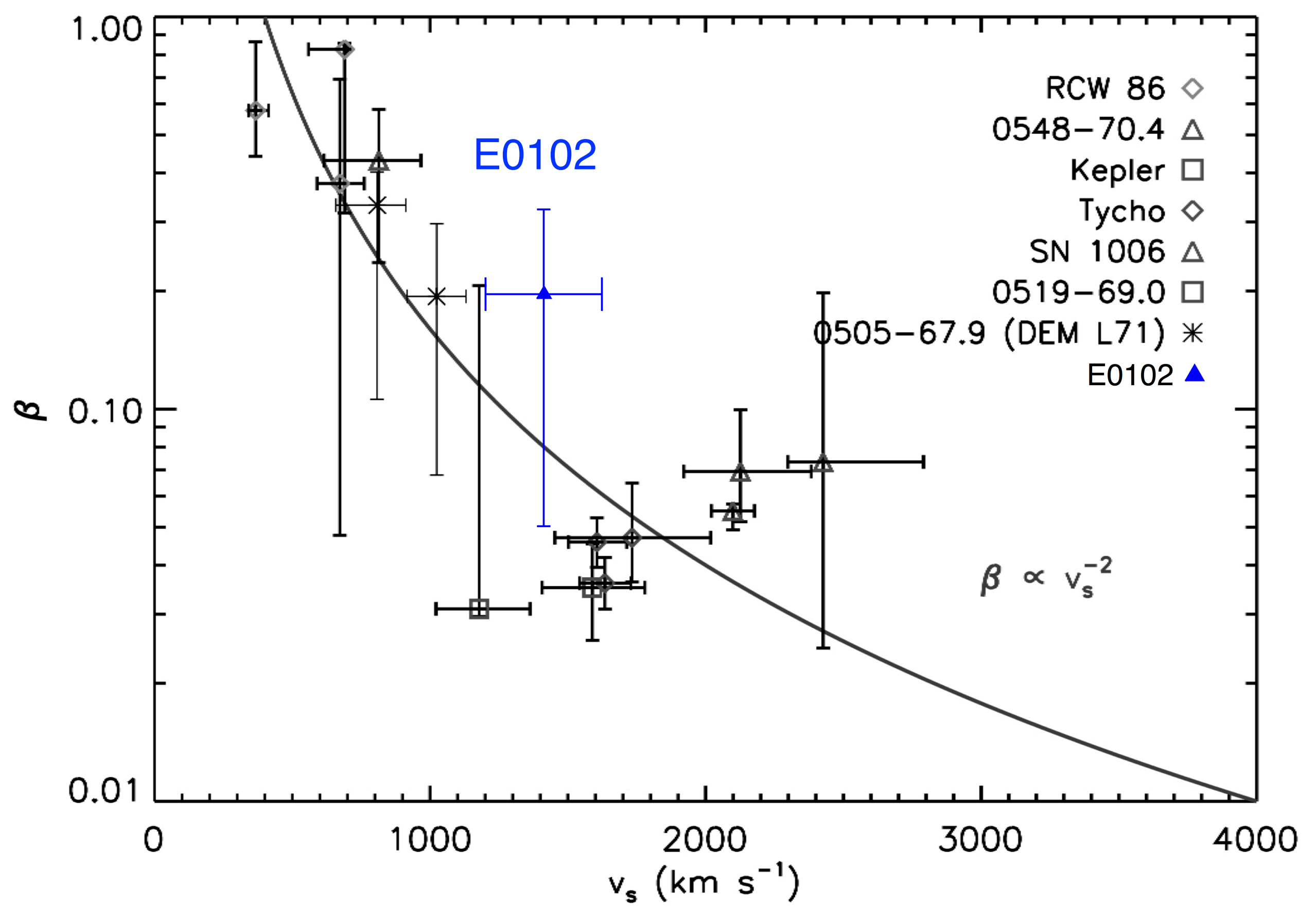
Figure 6: Radial Profile from OBSID 17380 for angle=292.5.



Results and Discussion

Our expansion results are shown in Figure 7 for the 11 observations included in this analysis. We measure an expansion rate of 0.0264 +/- 0.0043 % yr^{-1}, which is approximately four times smaller than what Hughes et al. measured. Our expansion rate is closer to what was measured in the optical by Finkelstein et al. Our expansion velocity of 1655 +/- 270 km s^{-1} is lower than the optical expansion velocity of 1966 +/- 193 km s^{-1}. This can be explained if the outer blast wave had a higher velocity in the past and has experienced significant deceleration. If we assume that the optical filaments have not experienced any deceleration, the deceleration parameter for the outer blast wave is ~0.5. This indicates that E0102 is evolving from the free expansion phase to the Sedov phase. We compare the ratio of the electron temperature to the proton temperature we measure to those tabulated in van Adelsberg 2008 in Figure 8. E0102 is rather consistent with the other remnants indicating that our measured ratio can be explained with a modest amount of electron/ion equilibration observed in other remnants.

Figure 8: Ratio of electron to ion temperature compared to other remnants, taken from van Adelsberg et al. 2008.



Spectral Extractions

We extracted spectra from the NE region of the blast wave, a region just outside of the bright X-ray ring and the central knot that was used for the registration. The regions are shown in Figure 2 and the blast wave spectrum and the near-ring spectrum are shown in Figures 3 and 4. The spectral data were fit with a "vpshock" model to estimate the temperature and abundances of the plasma. The fit results are displayed in Table 1. The blast wave spectrum has a temperature of ~0.76 keV with abundances typical of the interstellar medium in the SMC. The other two spectra have significantly enhanced abundances of O, Ne, and Mg.

Figure 2: Spectral extraction regions for the blast wave, region near the bright ring and the central knot.

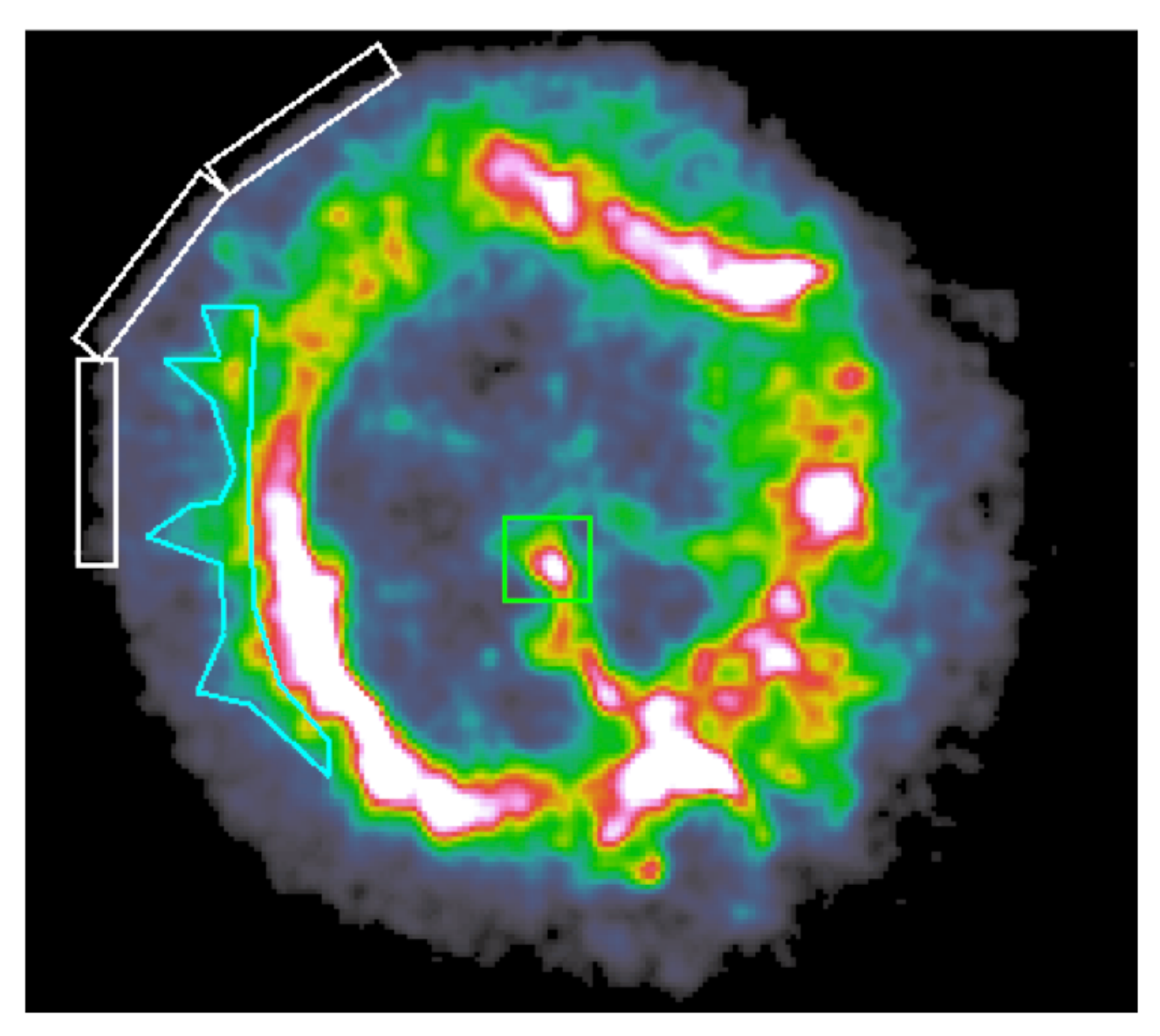


Figure 3: Blast Wave spectrum

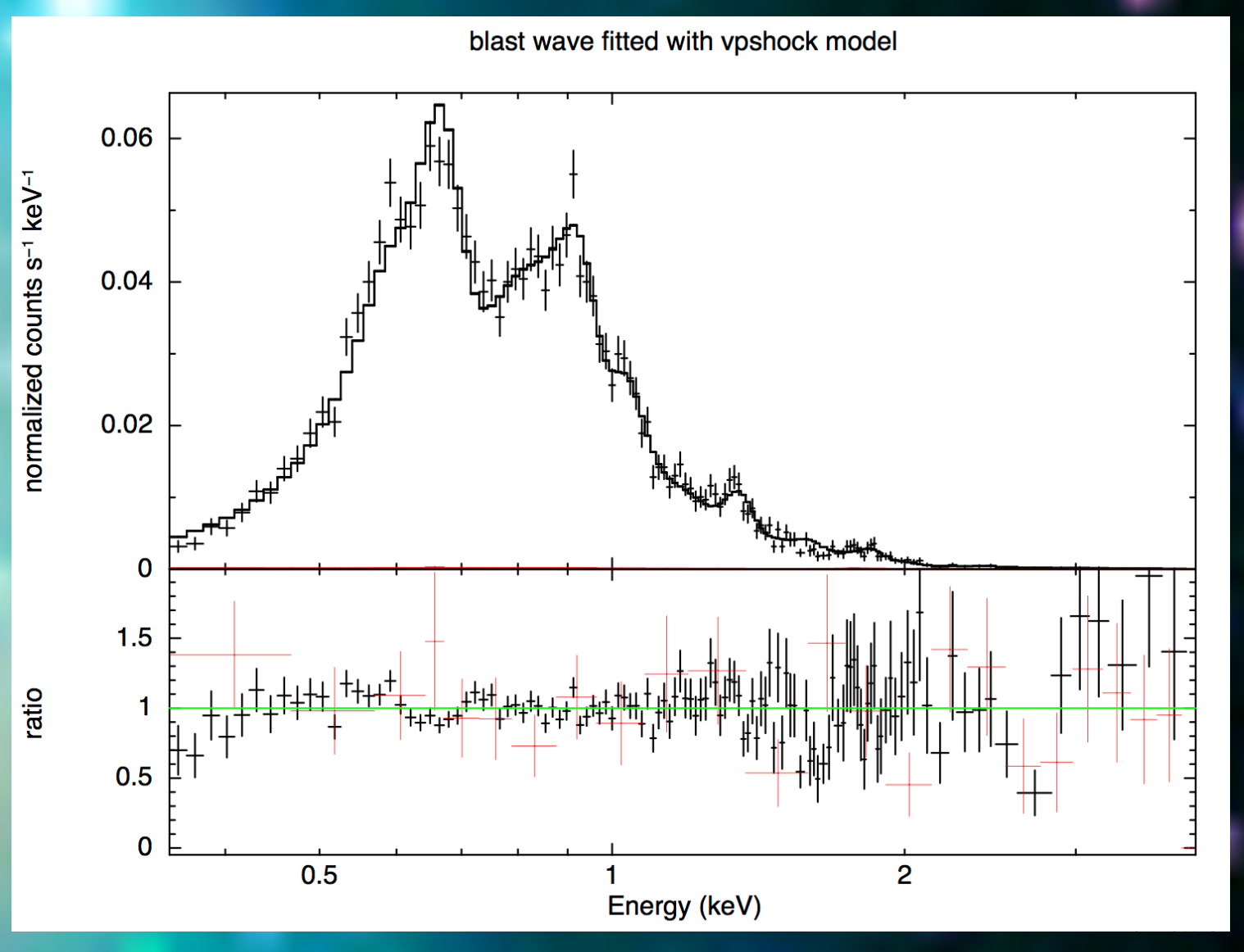


Figure 4: Near Ejecta Ring spectrum

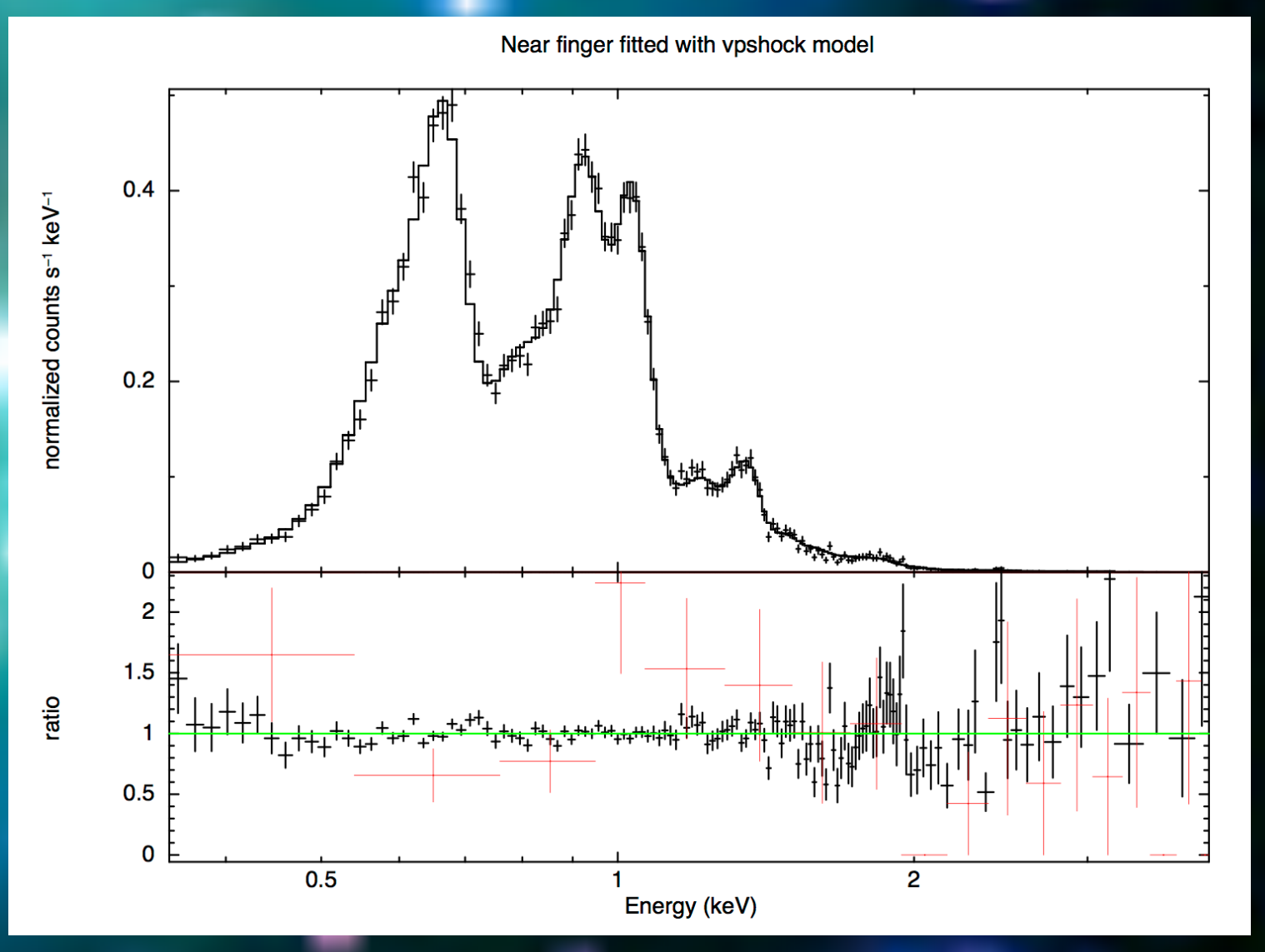


Table 1: Spectral Fit Results

Parameters	Blast wave	Ejecta	Center bright feature
kT(keV)	0.76 ± 0.05	0.63 ± 0.02	1.17 ± 0.08
$n_et(10^{11}cm^{-3}s)$	1.81 ± 0.32	9.05 ± 1.18	1.66 ± 0.32
$N_{H,SMC}(10^{20}cm^{-3})$	4.85 ± 1.81	6.81 ± 1.18	6.17 ± 0.88
Oxygen	0.29 ± 0.05	2.13 ± 0.28	2.46 ± 0.21
Neon	0.36 ± 0.04	3.02 ± 0.41	4.56 ± 0.36
Magnesium	0.27 ± 0.05	1.30 ± 0.18	2.23 ± 0.21
Iron	0.13 ± 0.02	0.1 ± 0.02	0.19 ± 0.06
$C-statistic$(dof)	553.25(488)	503.13(488)	664.17(488)

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