Supernova 1006

Tomáš Plšek
F9888: High Energy Astrophysics

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Analyze the data of Supernova 1006 observed in years 2003 and 2012 and determine how fast the supernova remnant is expanding:

1) process the datasets, create some images in different bands
2) create a residual image by subtracting images
3) determine expansion rate in pixels/years
4) use geometry to convert this rate to km/second
5) (optional) try extracting narrow bands of some high and low Z elements and see how they are dispersed through the remnant

1 Data reduction

I used the CIAO[1] software to both obtain and process the data of Supernova 1006. The datasets were reprocessed using the `chandra_repro` command and reprojected and merged via `merge_obs` command with binsize of 4 pixels. The images were extracted in both the broad band (0.5-7.0 keV) and CSC band (Chandra Source Catalog), which divides the whole energy range into 3 bands: soft (0.5-1.2 keV), medium (1.2-2.0 keV) and hard (2.0-7.0 keV). The broad band images were used to determine the expansion velocities of the supernova remnant. From images in the CSC band I created the false-color RGB image (Figure 1) using the DS9[2] program:

```
ds9 -rgb -red soft_flux.img -green medium_flux.img -blue hard_flux.img -rgb lock
scale yes -rgb lock smooth yes -log -smooth
```

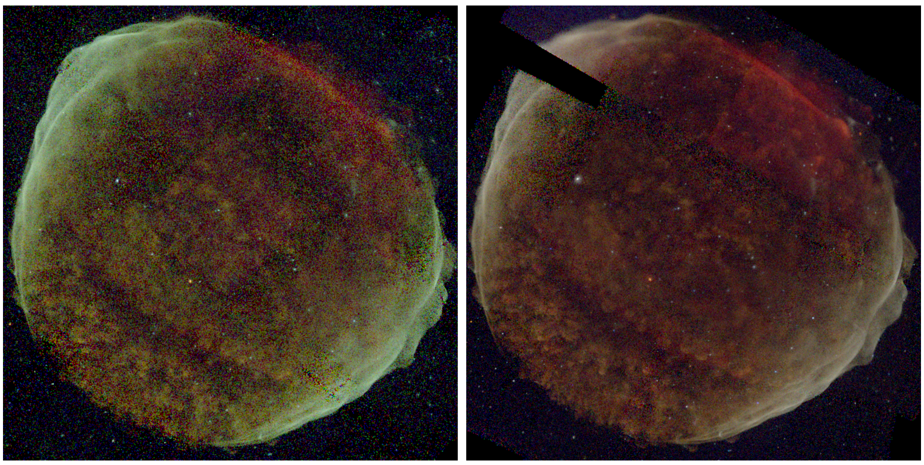

Figure 1: False color RGB images of SN1006 from years 2003 (left) and 2012 (right).

[1]https://cxc.harvard.edu/ciao/
[2]https://ds9.si.edu

I identified a bright point source on broadband images from both observing years (2003, 2012) and using its physical coordinates I shifted one image to match the other. Unfortunately, this method might be inaccurate to approximately the size of a bin (4 pixels $\approx$ 2 arcsec) and also biased by our choice of the source and the corresponding bin. I also tried to use the box region (DS9) with `fk5` coordinates to crop the images so their sky coordinates match and the images are the same sizes when subtracted. (This will probably round the number of pixels to an integer and not interpolate the images, so there is still the one-bin-size uncertainty, but at least it is not biased by choice of the highest pixel in a source. Do you think this way is better than matching on a point source by eye?)

2 Expansion velocity

To determine the velocity of expansion (aka the distance by which the remnant expanded) I used two different approaches: I determined the size of the rim by eye and also measured the distance using brightness profile. In both approaches, I used the residual image (Figure 2).

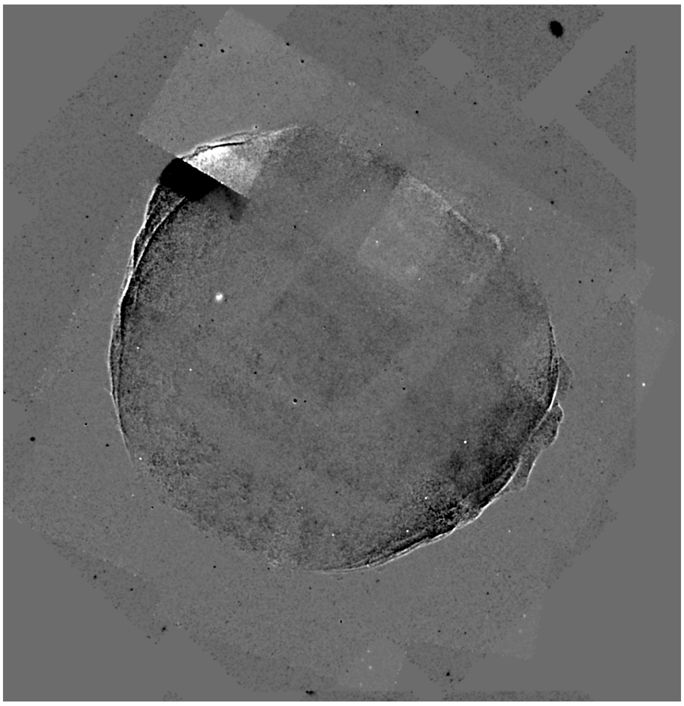

Figure 2: Residual image created by subtracting measurements from years 2012 and 2003.

2.1 Size of rim by eye

When subtracting the older image (2003) from the newer one (2012) a bright rim appears, which shows about how much the remnant has expanded. The width of the bright rim divided by the time difference between the observations should tell us the velocity at which the material expands:

$$v = \frac{s}{t} = \frac{\Theta\,[\mathrm{rad}] \cdot d\,[\mathrm{km}]}{9\,\mathrm{yrs}\,[\mathrm{s}]}, \tag{1}$$

where Θ is the angular size of the rim and d is the distance of the object. To estimate the width of the rim I smoothed the residual image with Gaussian kernel with 1-pixel radius (so it does not change the size of the features) and used the ruler shaped region in DS9 and by eye determined the angular size (Figure 3). The measurement was repeated 10 times so the result is more statistically correct. This way I measured 3 regions on different sides of the supernova remnant: west, east and south-west.

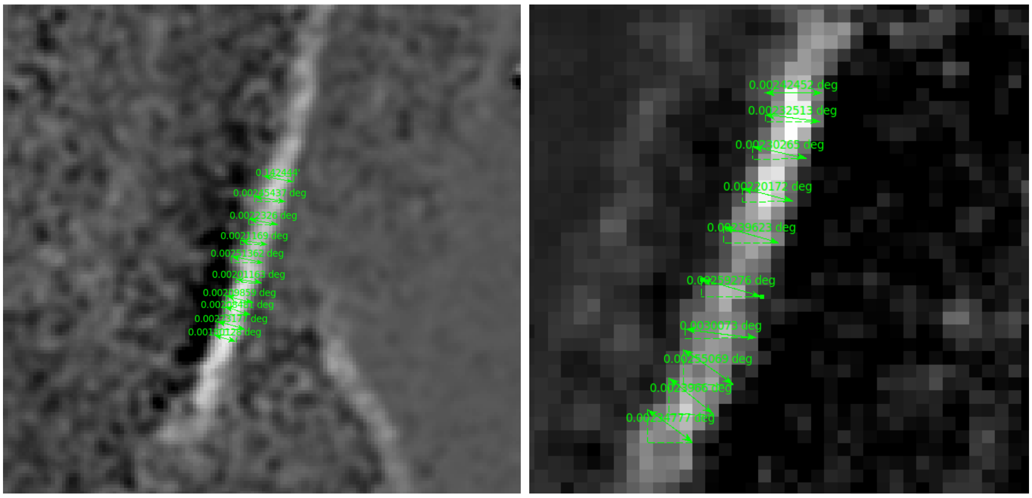

Figure 3: Zoomed residual image of the W and E rims. The green lines are the ruler regions used to measure the width of the rim.

Using this method I got the following results:

$$\begin{array}{rl} \text{West:} & \Theta = 7.2 \pm 0.5\ \text{arcsec},\ v = 8270 \pm 560\ \text{km/s} \\ \text{South-West:} & \Theta = 4.7 \pm 0.5\ \text{arcsec},\ v = 5340 \pm 590\ \text{km/s} \\ \text{East:} & \Theta = 8.8 \pm 0.8\ \text{arcsec},\ v = 10100 \pm 880\ \text{km/s} \end{array}$$

2.2 Distance from brightness profile

I tried also a different approach to determine the size of the expansion: to construct a brightness profile passing through the rim. The images were again smoothed with Gaussian kernel with a 1-pixel radius so the noise is at least a bit smeared out. To obtain the brightness profile the panda-shaped regions (DS9) were used (Figure 5). On some parts of the original images are visible bright rims, so after the subtraction, areas which were bright rims in 2003 will have negative values in the residual image. So I measured the distance from the "valley" to the "hill" in the brightness profile (Figure 4).

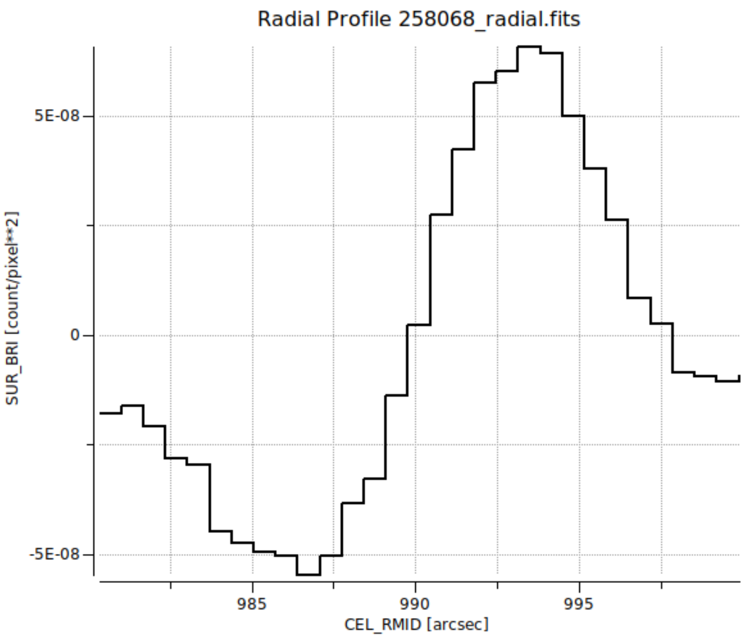

Figure 4: Brightness profile across the bright rim in the residual image.

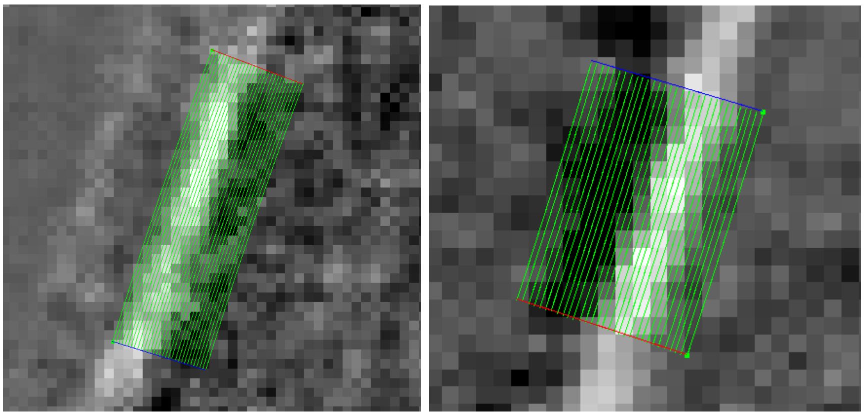

Figure 5: Western (left) and eastern (right) rims with the panda region, which was used to obtain the brightness profile.

Velocity from maximum-to-minimum distance:

$$\begin{aligned} \text{West:} \quad & \Theta = 6.7\,\text{arcsec}, \; v = 7700 \pm 250\,\text{km/s} \\ \text{South-West:} \quad & \Theta = 8.0\,\text{arcsec}, \; v = 9100 \pm 290\,\text{km/s} \\ \text{East:} \quad & \Theta = 9.8\,\text{arcsec}, \; v = 11200 \pm 360\,\text{km/s} \end{aligned}$$

3 Narrow band images

The narrow band images were extracted for 4 different elements: oxygen (0.65 keV), magnesium (1.34 keV), neon (0.92 keV) and silicon (1.85 keV) and smoothed.

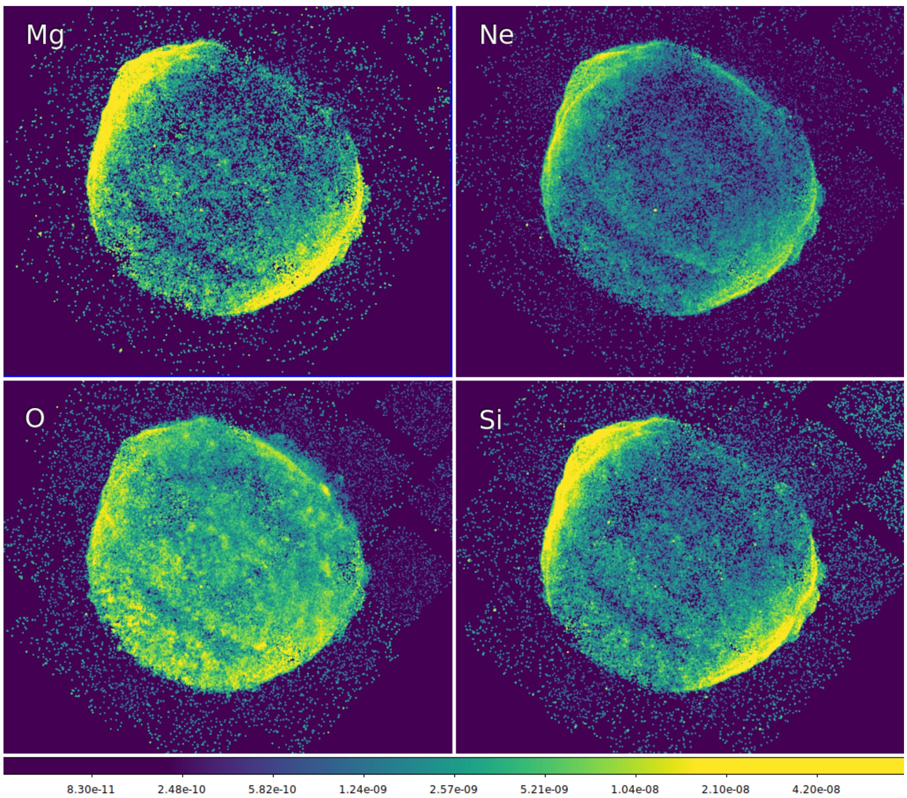

Figure 6: Narrow band images for various elements.

4 Conclusion

For the Western rim, I measured the expansion velocity around 8000 km/s, whereas in the literature (Winkler et al. 2014) they've got value around two times lower – 3000 km/s in the North-West and 5000 km/s in the South-West. At the Eastern edge, I measured velocity higher than 10 000 km/s, in the literature they've got velocity around 7400 km/s. The discrepancy might be due to different methods used for estimating the distance. In Winkler et al. (2014) they created brightness profiles from original observations and then fitted the radial range so the profiles matched.

From the Figure 6 is well visible that, whilst the oxygen is relatively equally dispersed across the supernova remnant, other elements (Mg, Ne, Si) are more concentrated in the NE and SW bright edges. The heavier the element is the more it is concentrated in the bright rims (it would be more obvious if I plotted the elements ordered according to their nucleon number). Also, the distribution of oxygen looks much more clumpy than for other elements.

References

Winkler, P. F., Williams, B. J., Reynolds, S. P., Petre, R., Long, K. S., Katsuda, S. & Hwang, U. (2014), 'A High-resolution X-Ray and Optical Study of SN 1006: Asymmetric Expansion and Small-scale Structure in a Type Ia Supernova Remnant', *ApJ* **781**(2), 65.