3D Visualisation of Integral Field Spectrometer Data

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A tool is presented for analysing integral field spectrometer three-dimensional datacubes by rendering the data in 3D with volumetric display techniques. Volume rendering can highlight features and aid the discovery of characteristics of astronomical objects that may not be easily detected with the more common two- and one-dimensional image and spectroscopy analysis tools. Examples of volume analysis are described, including Keck OSIRIS IFS data for the classical nova, V723 Cas, which exhibits a ring structure in its nova shell, and a 3D representation of observations of the supernova SN 1987a based on VLT SINFONI data.

Integral field spectrometer (IFS) instruments have been deployed at many observatories in recent years and are becoming very popular for a wide range of observational programmes. An IFS provides the ability to obtain spectra over the full extent of the instrument's field of view, removing the limitations of a slit as in conventional spectrometers. The IFS also preserves the spatial image information over the full spectral bandwidth. The resulting data product is a three-dimensional cube that contains a spectrum for every pixel in the image and an image at every element of the spectrum. The enhanced capability comes with an increase in the complexity of the data reduction and data analysis.

IFS instruments are very dependent on data reduction pipelines to support users, both in terms of real-time data assessment and offline data processing to facilitate scientific publication. Since mainstream use of IFS instrumentation is relatively recent, analysis tools are continuing to develop and astronomers are finding that working with these rich datasets can sometimes be challenging. The goal of the data processing and analysis, of course, is to extract as much science as possible. The pipeline data product of an IFS is typically a three-dimensional FITS file. These FITS files can be displayed using various tools, but it can be challenging to visualise cubes on a two-dimensional screen. A typical display tool will restrict the user to seeing either the spectra or the image in a single graphic. This article describes an approach to visualising data that employs a volume display that renders both spatial and spectral information simultaneously. The volume visualisation can reveal features that may be difficult to discover using other techniques.

Volume display tool

Two examples of IFS instrumentation for use at large telescopes include SINFONI (Eisenhauer et al., 2003; Bonnet et al., 2004) installed at the Very Large Telescope (VLT) and OSIRIS (Larkin et al., 2006) installed at the W. M. Keck telescope. Both of these instruments take advantage of the high spatial resolution of adaptive optics systems.

A volume-rendering tool was developed to analyse data for IFS instrumentation that can be used either with OSIRIS or SINFONI data. The tool[1] is coded in IDL and takes advantage of IDL's object-oriented volume-rendering routines. A set of tools for manipulating a datacube is configured in tab widget format. A screen grab of the tool is shown in Figure 1. The spectrum in Figure 1 is the longer wavelength subset of the K-band, using the Kn5 OSIRIS filter. The spectrum is of the classical nova, V723 Cassiopeia or Nova Cas 1995 observed in 2007. The volume display of V723 Cas data shows a continuum from the central point source and very bright coronal emission features from the nova ejecta (ring-shaped). The bright emission line is from [Ca VIII] 2.3214 μm. The emission feature is spatially resolved from the expanding nebula ejected from the nova (see Lyke and Campbell [2009] for a more detailed description of the OSIRIS study of V723 Cas).
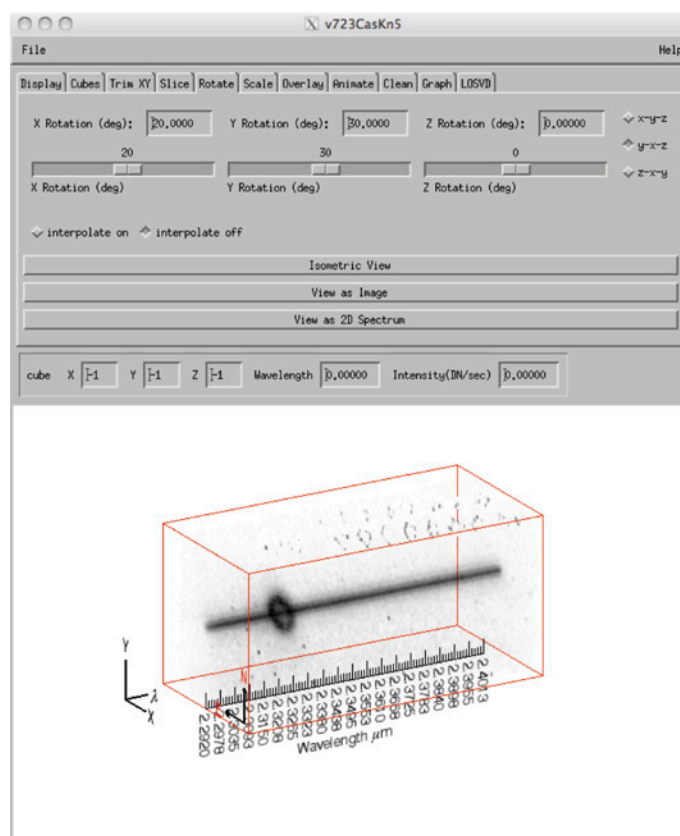

Figure 1. Screenshot of the 3D volume-rendering tool for IFS data. The display shows a continuum and a bright emission feature from the classical nova, V723 Cas. The continuum is from the central point source, but the emission feature of the [Ca VIII] fine structure transition is from the spatially resolved nova shell. The spectral coverage is of a portion of the K-band from 2.29 to 2.40 μm.
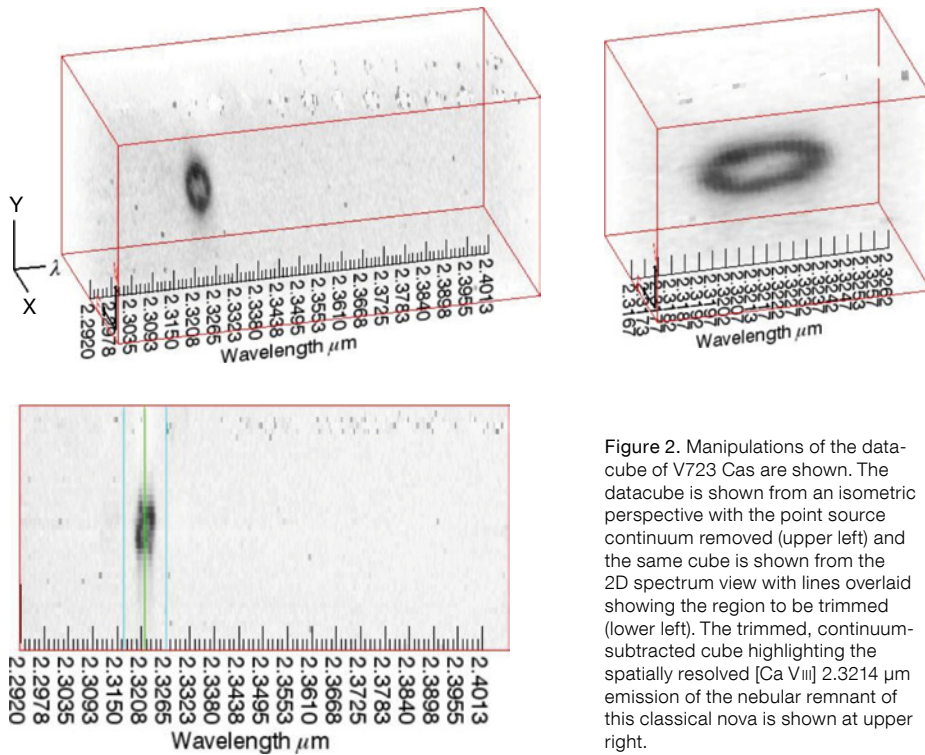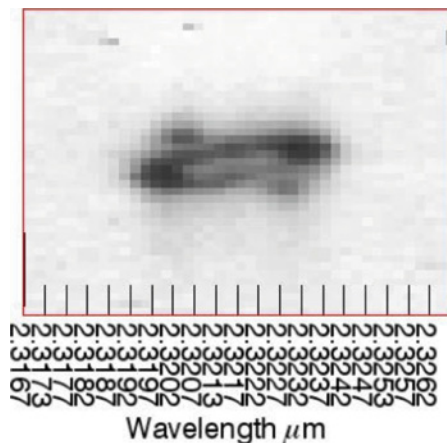
Figure 2. Manipulations of the data-cube of V723 Cas are shown. The datacube is shown from an isometric perspective with the point source continuum removed (upper left) and the same cube is shown from the 2D spectrum view with lines overlaid showing the region to be trimmed (lower left). The trimmed, continuum-subtracted cube highlighting the spatially resolved [Ca VIII] 2.3214 μm emission of the nebular remnant of this classical nova is shown at upper right.

Classical nova example

Expansion parallax is a technique for determining distances to various subsets of astronomical objects. For example, when an object such as a supernova or a classical nova is observed following an outburst event and both the radial veloc-ity and the angular expansion can be measured, the distance can be deter-mined relatively accurately with only a few simple assumptions about the shape of the ejecta. An IFS coupled with adaptive optics (AO) affords the capability to cap-ture both the velocity and the expansion simultaneously, thus improving the preci-sion of the distance measurement (Lyke, 2009).

An IFS 3D datacube is a measurement of intensity as a function of spatial extent and wavelength. When the distance to an object and the start time of the expan-sion are known, then the three axes of the cube can be converted into units of length in order to visualise the true shape of the object. The units of the two spatial dimensions are converted from angle on the sky to length based on the conver-sion of arcseconds to astronomical units (AU). The extent of the nova shell in the line-of-sight dimension can be computed from its expansion velocity measured directly from the Doppler shifted lines in the spectra. Once all three dimensions have been converted to units of length, the cube size is adjusted such that each side is the same size, thus rendering
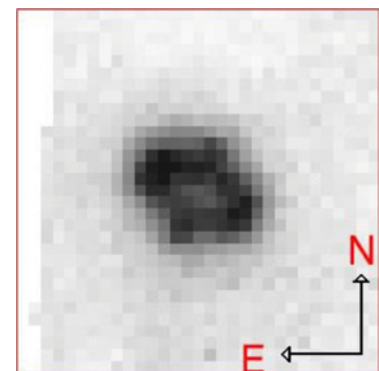
The volume tool has features that make it convenient for manipulating datacubes. The cube can be rotated to any per-spective in the *xyz* viewing angle. It has options for input and output of data as well as various features for adjusting dis-play parameters like stretch and colour. Other features include graphics overlays, axis display, zoom adjustment, aspect ratio adjustment and the ability to blink the display between multiple datasets.

The volume tool can easily be used to trim a cube in either the spatial or the spectral dimension. Trimming the cube can help to emphasise a region of inter-est, since a volume display can a have a significant region of noise that tends to "muddy" the view. Slicing in the spectral dimension is essentially customising a narrowband filter to highlight only the bandpass of interest. Figure 2 demon-strates a few of the cube manipulation abilities on the [Ca VIII] 2.3214 μm feature of V723 Cas. The unresolved point source continuum of V723 Cas has been re-moved here, leaving only the spatially resolved emission of the nova.

With the IFS volume tool, a cube can be manipulated in many ways. The volume can be rotated in any of the three dimen-sions so that the cube can be viewed from any angle, including the classical views of an image or as a two-dimen-sional spectrum (Figure 3).

Figure 3. A 2D spectrum view (left) and an image view (right) of the [Ca VIII] emission highlighting the spatially resolved velocity structure of the V723 Cas nova shell.
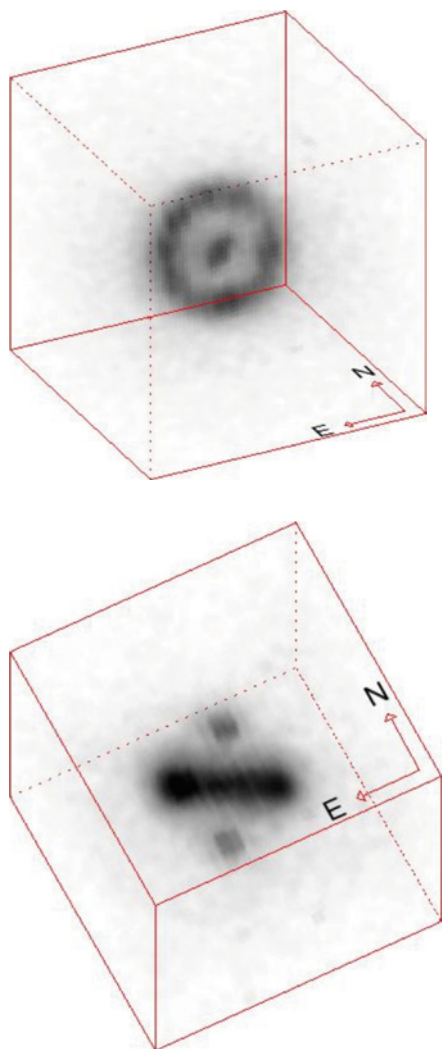
Supernova example

Although the tool was originally developed at Keck for use on OSIRIS data, it was subsequently adapted for use on SINFONI data with some relatively minor modifications. The work associated with adopting the tool for SINFONI was done during the summer of 2011 while the lead author participated in the ESO visitor programme in Garching. Supernova SN 1987a is one of the objects to which we are interested in applying the 3D analysis. This supernova is well suited for this purpose since the distance to the object is fairly well constrained due to its location in the Large Magellanic Cloud and the time of the eruption is very well known. Having good values for these parameters potentially allows the morphology of the ejecta to be rendered in 3D since the cube dimensions can be converted to units of length.

However, 3D analysis of SN 1987a is proving to be challenging for several reasons. The primary difficulty is the great distance to the object (50 kpc), which of course makes detecting and resolving the shell much more difficult. The observations must be taken long enough after the explosion to allow the shell time to expand to the point where it is large enough resolve from Earth, even with a

large telescope equipped with AO. However this delay gives the nebular material time to cool, become more rarefied, and diminish in brightness. Yet another challenge is the fact that the emission spectrum of SN 1987a has multiple components, due to the rings that existed prior to the explosion in 1987. The rings emit in some of the same wavelengths as the supernova ejecta, but have a very different velocity structure and different relative line strengths. The multiple sources of emission are difficult to disentangle in the integral field spectra.

SINFONI data acquired in 2005, and subsequently reduced using the instrument pipeline, were input to the IFS volume tool. The data in this example are over a narrow region of the H-band centred on a [Si I]+[Fe II] emission line blend at 1.644 µm. Figure 5 shows the image view and 2D spectrum, displaying the spatially resolved supernova ejecta in the central portion as well as the inner ring surrounding it. A detailed analysis of the SINFONI study of SN 1987a is presented in Kjær et al. (2010). The 2D spectrum reveals the brighter and narrower emission lines that are from the inner ring, whereas the broader, Doppler-shifted features are from the high velocity ejecta. There are also several telluric features complicating this part of the spectrum.
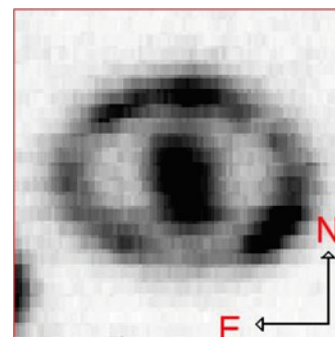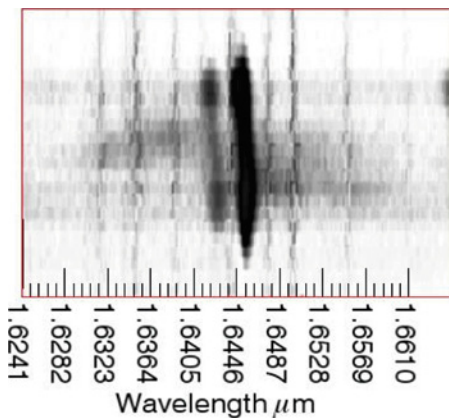

Figure 4. The true 3D morphology of the V723 Cas nebular remnant is shown. From the distance and time since eruption, the angular and velocity dimensions can be converted to create a cube with sides of equal units of length, in this case 3300 AU (5.0 × 10^{11} km). The 3D analysis clearly reveals the very distinct equatorial ring and polar "blobs" that are viewed both face-on (upper) and edge-on (lower) in the two different views.

the object in its true 3D morphology. Figure 4 shows the V723 Cas nova shell in [Ca V III] emission from two viewing angles, one perpendicular to an equatorial ring that has formed in the nebular shell, and one viewing the ring edge-on where polar knots become more evident. These features are much more evident in the 3D display and demonstrate the usefulness of this type of analysis.

Figure 5. The 2D spectrum view (left) and the image view (right) of SN 1987 is shown in the blended [Fe II]+[Si I] emission lines. Two sources of emission are distinguishable in the 2D spectrum and image view: the inner ring, visible as two relatively narrow lines in the spectrum; the much broader feature, Doppler-shifted by the high velocity ejecta, in the central regions.
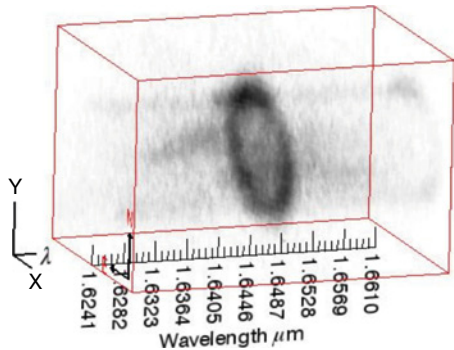
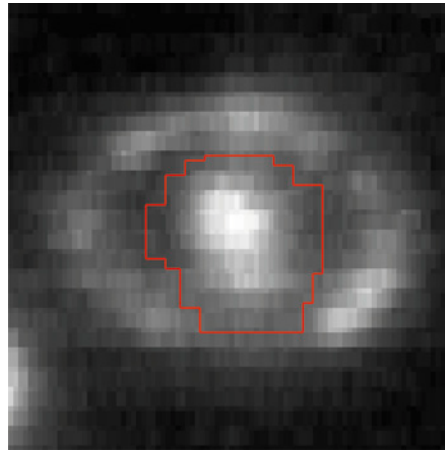Figure 6. 3D volumetric display is shown of [Si I]+[Fe II] blended line emission at 1.644 μm from SN 1987a.

Figure 7. Isolating the emission of SN 1987a ejecta from the inner ring emission. On the left, the spatial selection by cutting out the cube around a polygon, outlined in red, is shown. At right, the 2D spectrum of the polygon-selected cube region before (upper) and after (lower) subtraction of the peak emission from the inner cube is shown.

Figure 6 shows the volume display of the same datacube as Figure 5, but tilted such that the entire volume can be seen. This allows both the spatial and spectral dimensions to be shown in one graphic, the intent of which is to help reveal subtle features that may not be apparent in the 2D views of the data. However, SN 1987a does not give up its characteristics easily and any new features that were not already discussed in Kjær et al. (2010) are not obvious in the volume rendering. It is presented here as an example to demonstrate the potential capability of analysing SINFONI data in this manner.

Nevertheless, additional processing was attempted to separate the ring emission from the ejecta such that the true 3D shape of the supernova shell could be visualised. Figure 7 shows a region spatially cut from the original cube outlined by a polygon. Additional processing included a Gaussian fit to the peak narrow line of each spectrum of the cube that was then subsequently subtracted to help reduce the flux contribution from the inner ring. Figure 7 shows a comparison of the two 2D spectra with and without the removal of the bright line. The processing helps to isolate the ejecta from the other sources within the original datacube.

Figure 8 shows a rotated volume display of the fully processed cube. The dimensions of the cube are approximately 3.0×10^{12} km on a side. Unfortunately, it is hard to derive a definitive shape of the ejecta from the volume display due to its complex and diffuse nature. The 3D graphic only gives a hint of the morphology, one that is consistent with the conclusion in Kjær et al. (2010) of the SN ejecta with its asymmetric lobes expanding at different angles. The 3D analysis of SN 1987a has proved to be significantly more challenging than that of the classical nova V723 Cas. The V723 Cas data has much brighter coronal lines in the *K*-band where telluric features are less of an issue. The SN 1987a data are much more complex with blended lines of very high velocities within a forest of telluric OH lines. Nevertheless, SN 1987a is one of the most compelling objects in the nearby Universe and thus any attempt to understand its true nature is worthwhile.

References

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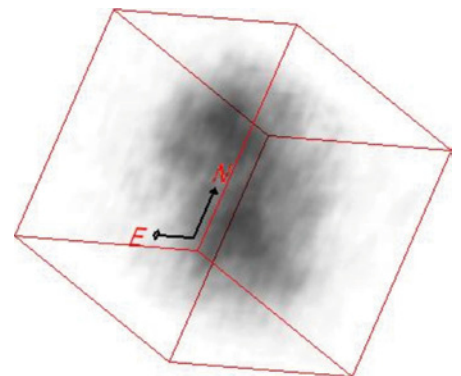Lyke, J. & Campbell, R. 2009, AJ, 138, 1090
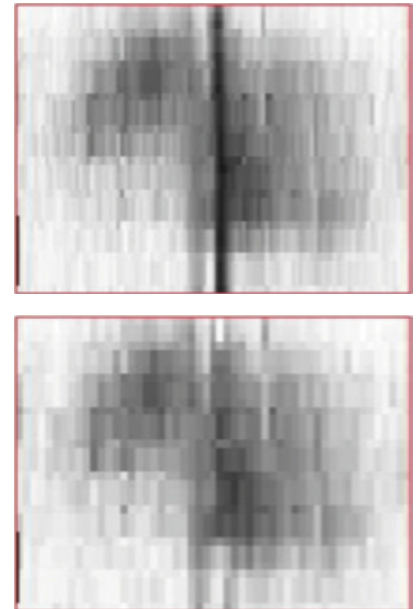
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Figure 8. 3D spatial representation of SN 1987a, isolating the blended [Si I]+[Fe II] emission lines of the shell from the inner ring, is shown. This visualisation highlights the asymmetric nature of the shell as determined in Kjær et al. (2010). The cube dimensions are approximately 3.0×10^{12} km on each side.