Optical Integral Field Spectroscopy Study of Supernova Remnants

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ABSTRACT

The study of supernova remnants (SNRs) is key to our understanding of various unsolved problems in astrophysics. These include: the supernovae explosion mechanism, the properties of the stellar progenitors, the heating and the chemical enrichment of the interstellar medium (ISM), and the fate of stars following their death. The relatively new domain of integral field spectroscopy has transformed observational spectroscopy, and in particular, has revived the SNRs research in the optical regime. It has enabled the studies of SNRs in much depth: providing high-resolution spectroscopy of SNRs allowing us to put constraints on their nature and their interaction with their surroundings. In this paper, we summarize the powerful potential of integral field optical spectroscopy of SNRs, highlighting our group's ongoing and future work in this area.

Keywords: *Integral field spectroscopy – Supernova remnants – Neutron stars*

1 SUPERNOVAE AND SUPERNOVA REMNANTS

The word "super-nova" was first introduced by Walter Baade and Fritz Zwicky in their 1934 series of papers, to refer to *the transition of an ordinary star into a neutron star* (see Baade & Zwicky, 1934a,b,c). We now classify supernovae (SNe) into two major classes: the 'core-collapse SNe' that occur when massive stars (of initial masses ≥ 8 $M_\odot$) reach their last evolutionary stages and collapse to form a neutron star or a black hole, and the `thermonuclear (or type Ia) SNe' when white dwarfs in binary systems are triggered into runaway nuclear fusion which generally destroys the progenitor star; see Chevalier (1996) for an early review.

Following the supernova explosion, the ejecta spill out into space forming the beautiful diffuse nebulae that we see for approximately 100,000 years following the explosion, the Supernova Remnants (SNRs). Supernova explosions are among the most energetic events in the universe, releasing about 10^{51} erg of kinetic energy into the interstellar medium (ISM) and scattering in space the heavy elements fabricated during the star's lifetime and the SN explosion. As well, SNR shocks contribute to cosmic ray acceleration to very high energies. As such, SNe significantly influence the chemical content and dynamics of the ISM, and depending on the density of the ISM and the shock velocity, supernova explosions could either trigger or suppress star formation (e.g. Nagakura et al. 2009; Booth & Schaye, 2013).

Despite many fields in astrophysics (both Galactic and Extragalactic) using and depending on supernovae, the nature of their progenitors, explosion mechanism and particularly their aftermath continues to be debated. Much can be learned from studying and zooming in on nearby events. Due to the rare occurrence of observable supernovae in our Galaxy, we can focus our study on SNRs which remain visible for thousands of years post stellar death, providing us with nearby laboratories to trace the observable SNRs back to their SN engines. In particular, the nature of the shocked interstellar medium, its emission lines characteristics, spatial distribution and progenitor imprints (such as an associated compact object) hold important clues about the supernova progenitors and aftermath.

1.1 Central Compact Objects

An intriguing aspect that makes studying SNRs crucial is their compact objects leftovers. Progenitors that survived the (core-collapse) supernova explosions collapse into either neutron stars or black holes, depending on their initial masses. Among the many different subclasses of neutron stars that have been observed in the past few decades, there is a particularly unique class of isolated neutron stars detected in X-rays near the SNR centres, called `Central Compact Objects' (CCOs; for review see De Luca, 2017 and Safi-Harb, 2017).

This unique class, whose nature and progenitors continue to be debated, provides us with important clues about the diversity of SNe and their aftermath. CCOs have been dubbed as `anti-magnetars' (Gotthelf et al. 2013) given their relatively low surface dipole magnetic fields (~10^{10} G, compared to 10^{12} G of the average neutron stars or $10^{14\text{-}15}$ G for magnetars) inferred from timing a few objects of the sample. CCOs are exclusively visible in X-ray and so far, they have no identified counterparts at any other wavelength. Furthermore, their characteristic ages are orders of magnitude larger than their hosting SNRs' ages (about 2 to 5 orders of magnitude larger). These unique properties have been addressed through invoking fallback from the SN burying their magnetic field and through magnetic field evolution in neutron stars (Ho 2011, Rogers & Safi-Harb 2016). Furthermore, addressing their explosion properties and progenitors through recent X-ray observations of their associated SNRs has so far led to lower mass progenitors and explosions (see e.g., Braun et al. 2019). As described below, modern optical studies of this sample are needed as they provide further important clues on their birth properties and environment.

1.2 Optical Studies of Supernova Remnants

Long before the SNR field was born, several Galactic SNRs were known as optical nebulae to astronomers. Their optical spectra are dominated by line emission, in particular Hα, and forbidden line emission of nitrogen, oxygen, and sulfur. The presence of these forbidden lines indicates strong cooling behind the shock front (i.e. radiative shocks; Seward & Charles, 1995) and is usually associated with mature SNRs.

However, not only mature SNRs display optical emission. Some young SNRs have dense clumps in their surrounding ISM, and as the shock waves penetrate these clumps, the shocks slow down and become radiative. There are also young SNRs located in a partially neutral medium whose spectra have no forbidden line emission, but show hydrogen Balmer lines (e.g. Heng, 2010; Vink, 2020). Lastly, optical studies of their associated compact objects can provide clues about their energetics and environment which is directly linked to their SNR hosts.

Imaging and spectroscopic studies of SNRs in the optical regime offer a unique opportunity to probe the explosion dynamics and progenitors, the nucleosynthesis process, the shock mechanism and the ambient medium conditions. Hence, studying the SNRs, particularly the poorly studied-in-the-optical CCOs-hosting class, is needed to further constrain the basic parameters of these objects and addressing the diversity of SNe and their remnants (Chevalier, 1977; Safi-Harb, 2017).

2 INTEGRAL FIELD SPECTROSCOPY OF SUPERNOVA REMNANTS

Since its advent in the 1980s (Bacon & Monnet, 2017), radio astronomers have used integral field spectroscopy long before it was finally adopted in the optical regime. Integral field spectroscopy enables a more effective way to study astronomical objects, especially compared to the "traditional" aperture and long-slit spectroscopy.

In "traditional" spectroscopy, a single aperture or a slit is placed on the focal plane, then the light from the object goes through the slit and gets dispersed by the spectrograph onto the detector. The main disadvantage of this method is that only a point or a line through the object is sampled at the same time. In order to cover a full extended object, it requires several consecutive exposures, sometimes with altered slit positions. This is not only time-consuming, but also prone to errors in pointing when doing different exposures.

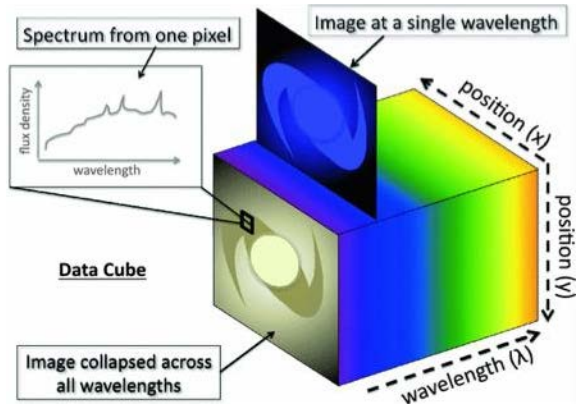

Figure 1. The schematic diagram of a datacube (Harrison, 2016). A datacube provides information in three dimensions: two spatial dimensions (most commonly right ascension and declination) and a third dimension of wavelength.

Integral field spectroscopy aims at addressing these aforementioned problems by allowing spectroscopy and imaging of a two-dimensional area of an image plane to be done simultaneously. As the spectrum of each spatial element is taken at the same time, the result is more stable and uniform. This is how integral field spectroscopy provides an efficacious solution for astronomical spectroscopic studies.

This technique produces spectra of each spatial point of a two-dimensional field, which then generates a three-dimensional data product called a datacube. A datacube is essentially a stack of many images at different wavelengths of the same plane of the sky (see Figure 1). With integral field spectroscopy, astronomers are able to study astronomical objects in a novel and more effective way, especially if the objects have complex structures or there are many objects in the same field of view.

2.1 Recent Breakthrough

Integral field spectroscopy has revived SNRs research at optical wavelengths. Studying SNRs with the integral field spectroscopy approach has recently shown its incredible potential. For example, it has allowed the study of dust destruction in SNR shocks (Dopita et al. 2016), the investigation of important diagnostics for the cosmic-ray acceleration efficiency in SNR shocks (Ghavamian et al. 2017), the discovery of new elements in the SNR ejecta (Seitenzahl et al. 2018, 2019), and the three-dimensional reconstructions of SNRs structure (Martin et al. 2021).

One of the recent relevant highlights of integral field spectroscopy capability in SNR research is the work done by Vogt et al. (2018). Using MUSE (Multi-Unit Spectroscopic Explorer on the Very Large Telescope, Chile; Bacon et al. 2010) data, a previously unknown compact remnant of the supernova progenitor of extragalactic SNR 1E0102.2-7219 was discovered. The compact remnant, believed to be an added CCO to the growing CCOs class, is embedded in an unexplained dense ring of cold gas, shining in the recombination lines of Ne I and O I. This would then indicate the first detection of a CCO through Integral Field Spectroscopy. However, there is an ongoing debate about the nature of the compact remnant (see Hebbar et al. 2020; Long et al. 2020; Banovetz et al. 2021). Regardless, this is the very first time that (optical) light on a CCO candidate identified in a SNR outside of the X-ray regime.

3 ONGOING AND FUTURE WORKS

The optical study is the oldest method to study SNRs, yet it has been limited by the unavailability of detectors that are sufficiently sensitive to reveal the most details in the SNRs spectra. With the promising powerful capabilities of integral field spectroscopy, our SNR group at the University of Manitoba aims to further tackle the unsolved problems in current SNR research.

Our main focus is to utilize the newly revealed potential of integral field spectroscopy observational data for SNRs research in the optical regime; specifically in order to find ways to understand the supernovae explosions mechanisms and the properties of the progenitors. The high-resolution spectral studies of SNRs will potentially provide new evidence dating back to the time of the explosions. There are several unsolved questions that we would like to address: what elements are produced by the supernovae explosions and what are their kinematics and morphological distributions?; what are the constraints we can infer from SNRs observations for the physical properties of the progenitors?; is there any optical signature of the compact objects we can observe and if so, what are their and their environment's physical properties?

3.1 SNR G266.2-1.2 (in prep.)

SNR G266.2-1.2 or Vela Jr. is a shell-type SNR that lies along the same line of sight as the larger Vela SNR. It is a young SNR with a CCO located at its geometric centre (CXO J085201.4−461753; see Aschenbach, 1998; Pavlov et al. 2001; Kargaltsev et al. 2002). Our MUSE data (4750 Å - 9350 Å) of Vela Jr. characterized a nebula that is strongly emitting in [N II], at the exact location of the known CCO. Together with the recent possible identification of a CCO in SNR 1E0102.2-7219, this is the first time that the CCOs and their interactions with their environment are observed in the optical wavelength. This opens a new door for CCO observations outside the X-ray regime.

Our data confirms with certainty that the feature, previously identified as an Hα nebula (Pellizzoni et al. 2002, Mignani et al. 2007), shines primarily in [N II]λλ6548,6583. The initial estimate indicates that the [N II] nebula must have a line of sight velocity of 60-80 km/s. We also identify a faint rim of Hα (see Figure 2) on the nebula and emissions from [S II]λλ6716,6731, and [S III]λ9068, along with [N I]λ5198+5200(blended), He I λ6678, [Ar III]λ7136, and [Fe II]λ8616.

Our MUSE data show that the [N II] abundances are much stronger than Hα, and that there is no [O

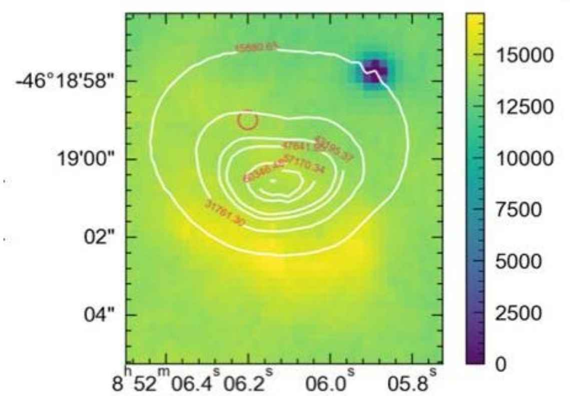

Figure 2. The intensity distribution of Hα emission with [N II] overlay in white (flux levels: 25%, 50%, 68%, 75%, 90%, 95%, and 99.7%). The red circle marks the Vela Jr. CCO's location and the coordinates are in J2000. The purple circle on the top right corner is the residual from the continuum subtraction process.

III] emission. Our new observations of Vela Jr. with MUSE will provide a better spatial resolution of the CCO nebula and a clearer view of the emission lines associated with the nebula. We will provide reliable flux calibration and an assessment of the connection between the nebula and the CCO, thus constraining the nature of the CCO and associated SN explosion.

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