RMxAC, **58**, 54–56 (2024)

ACROSS THE TYPE IA SUPERNOVA-VERSE: FROM TYPE IA SUPERNOVA REMNANTS TO BINARY LOVE STORIES IN THEIR PREVIOUS LIFE

Chuan-Jui Li[1] and You-Hua Chu[1,2]

RESUMEN

Las supernovas de tipo Ia (SNe Ia) se han utilizado como candelas estándar para descubrir la expansión acelerada del universo, lo que llevó a la revelación de la energía oscura y a la concesión del Premio Nobel de Física de 2011 a los astrónomos. Por importantes que sean, las SNe Ia no se comprenden completamente. Todavía discutimos sobre cómo explotan. No está claro si se originan a partir de: (1) un origen degenerado simple (SD) en el que las enanas blancas acretan de estrellas binarias compañeras o (2) un origen degenerado doble (DD) que resulta de la fusión de dos enanas blancas. Para investigar la naturaleza de SNe Ia, buscamos pistas sobre su vida anterior en los restos de explosiones, llamados remanentes de supernova (SNR). Si se detecta un compañero superviviente o un medio circunestelar denso debido a la pérdida de masa del progenitor, se puede afirmar el origen de la SD. Durante las últimas décadas, no se ha encontrado de manera inequívoca en la Vía Láctea ningún compañero superviviente dentro de las SNR Ia. Por lo tanto, decidimos ampliar los límites hacia otras galaxias. Utilizando imágenes y espectros de estrellas y gas ionizado, encontramos que el origen SD de SNe Ia podría ser más frecuente de lo que se pensaba anteriormente.

ABSTRACT

Type Ia supernovae (SNe Ia) have been used as standard candles to discover the accelerating expansion of the universe, leading to the revelation of dark energy and the award of 2011 Nobel Prize in Physics to astronomers. Important as they are, SNe Ia are not fully understood. We still argue about how they explode. It is not clear whether they originate from (1) a single-degenerate (SD) origin in which white dwarfs accreting from binary companion stars or (2) a double-degenerate (DD) origin results from mergers of two white dwarfs. To probe the nature of SNe Ia, we search for clues to their previous life in the remains of explosions, called supernova remnants (SNRs). If a surviving companion or a dense circumstellar medium from the progenitor's mass loss is detected, the SD origin can be affirmed. Over the past decades, no surviving companions within SNRs Ia have been unambiguously found in the Milky Way. We thus decided to push the envelope to other galaxies. Using images and spectra of stars and ionized gas, we find that the SD origin for SNe Ia could be more prevalent than people previously thought.

Key Words: ISM: individual objects (SNR 0509–67.5, SNR 0519–69.0, SNR 0509-68.7, SNR DEM L71, SNR 0548–70.4) — ISM: supernova remnants — Magellanic Clouds

1. INTRODUCTION

Type Ia supernovae (SNe Ia) have been used as standardizable candles to discover the accelerated expansion of the universe, leading to the revelation of dark energy and the award of 2011 Nobel Prize in Physics to Saul Perlmutter, Brian Schmidt, and Adam Riess. Important as they are, SNe Ia are not fully understood. People still argue about how they explode.

Generally speaking, two contrasting origins of SNe Ia have been suggested: a *single degenerate (SD)* origin in which a white dwarf accretes material from a non-degenerate normal star companion until its mass nears the Chandrasekhar limit (Whelan & Iben 1973; Nomoto 1982), and a *double degenerate (DD)* origin that results from the merger of two white dwarfs (Iben & Tutukov 1984; Webbink 1984).

It is still debated whether the SD or DD origin is prevalent among SNe Ia. In the SD scenario, the interaction between the white dwarf and the normal star companion strips the mass of the companion to form a circumstellar medium (CSM; Hachisu et al. 2008), and the companion can survive the SN explosion and be detected (Marietta et al. 2000; Pan et

[1]Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617, Taiwan.

[2]Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 West Green Street, Urbana,IL 61801, U.S.A.

al. 2014). In the DD scenario, both white dwarfs are destroyed and no dense CSM or detectable stellar remnant is expected. Therefore, if a surviving companion or a dense CSM is detected near the explosion center of a Type Ia SN remnant (SNR Ia), the SD origin of this SN can be affirmed (Ruiz-Lapuente 1997; Canal et al. 2001); however, to date, no surviving companion has been unambiguously identified near explosion centers of SNRs Ia, although dense CSM has been detected in some SNRs Ia (see Wang & Han 2012; Maoz et al. 2014; Ruiz-Lapuente 2014; Wang 2018; Ruiz-Lapuente 2019 for reviews).

To probe the nature of SNe Ia's progenitors, we have chosen the young SNRs Ia in the Large Magellanic Cloud (LMC) because of the known distance, low extinction, and minimal line-of-sight confusion. The young SNRs Ia exhibit shell structures whose optical spectra are dominated by Balmer lines with no or weak forbidden lines, as a result of collisionless shocks advancing into a partially neutral interstellar medium (ISM; Chevalier et al. 1980). The LMC hosts five SNRs Ia containing Balmer−dominated shells: 0509−67.5, 0519−69.0, N103B, DEM L71, and 0548−70.4, as shown in Figure 1. We have been studying these SNRs' structure and environments and searching for their SN progenitors' companion stars and the circumstellar medium, as summarized below.

2. SEARCH FOR SURVIVING COMPANIONS OF PROGENITORS OF YOUNG LMC SNRS IA

We used two different methods to conduct an extensive search for surviving companions of SN progenitors in all 5 SNRs Ia in the LMC. In the first method, we used the HST photometric measurements of stars to construct color−magnitude diagrams and compared positions of stars in the color−magnitude diagrams with those expected from theoretical post-impact evolution of surviving companions (e.g., Pan et al. 2014). In the second method, we used the Very Large Telescope (VLT) Multi Unit Spectroscopic Explorer (MUSE) observations to carry out spectroscopic analyses of stars in order to use large peculiar radial velocities as diagnostics of surviving companions.

In the SNR 0509−67.5, we found that no stars are near the explosion center and confirmed the absence of a surviving companion (Litke et al. 2017). In the other 4 SNRs Ia, N103B, DEM L71, 0519−69.0, and 0548−70.4, we carried out the photometric and spectroscopic analyses and searched for surviving companions. In addition to the candidate we found in

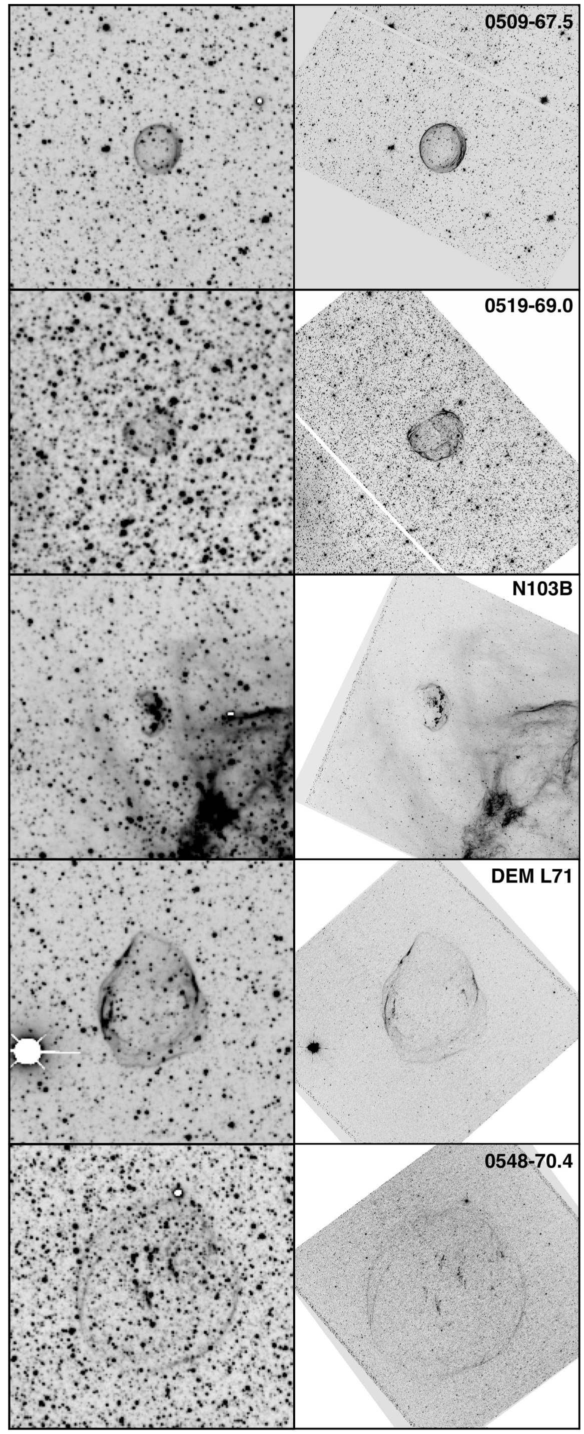

Fig. 1. Hα images of the five LMC SNRs Ia with Balmer−dominated shells (from Li et al. 2021). Left Images were obtained with the MOSAIC II camera on the Blanco 4 m Telescope at Cerro Tololo Inter-American Observatory and right images were taken with the Hubble Space Telescope. The field of view of each panel is 3'×3'. North is up and east is left.

N103B (Li et al. 2017), we found a star in 0519−69.0 and a star in DEM L71 with large peculiar radial velocities, making them possible candidates of surviving companions of the SN progenitors (Li et al. 2019). In this work, *we find that 20%− 60% of these five young SNRs Ia may originate from SD progenitors, significantly higher than the 20% previously suggested by González Hernández et al. (2012).*

2.1. *Search for Circumstellar Medium within Young LMC SNRs Ia*

SNRs are generally diagnosed by strong [S II] $\lambda\lambda$6716, 6731 lines, nonthermal radio emission, and diffuse X-ray emission, which are characteristics produced by fast shocks. However, young SNRs Ia show filamentary shells with optical spectra dominated by Balmer lines without forbidden-line counterparts. The weakness or absence of forbidden lines can be explained by collisionless shocks advancing into a partially neutral medium (Chevalier et al. 1980). In the case of N103B, bright forbidden lines are detected from dense knots that represent the CSM ejected by the progenitor before the SN explosion, implying that the SN progenitor must be of SD origin (Li et al. 2017).

Intrigued by the CSM in N103B, we used VLT MUSE and Advanced Technology Telescope (ATT) Wide Field Integral Spectrograph (WiFeS) observations to search for forbidden-line emission from all five SNRs Ia containing Balmer-dominated shells in the LMC: 0509−67.5, 0519−69.0, N103B, DEM L71 and 0548−70.4. We was pleasantly surprised to find bright forbidden line emission from small dense knots in 4 out of these 5 SNRs. *Dense nebular knots were discovered in 0519−69.0, DEM L71, and 0548−70.4 for the first time!* The electron densities of the dense knots are as high as 10,000 H cm^{-3}, suggesting that they originate from a CSM. Thus the presence of CSM in SNRs Ia seems prevalent, and *the physical properties of the CSM evolve along the SNR.*

From this work, we find that 80% of these five young SNRs Ia contain dense CSM and may originate from SD progenitors, consistent with my previous finding based on the search for surviving companions (Li et al. 2019). *These studies indicate that the SD origin for SNe Ia could be more prevalent than people previously thought (Li et al. 2021).*

3. SUMMARY

SNe Ia may originate from (1) a SD origin, in which white dwarfs accreting from binary companion stars or (2) a DD origin, that results from mergers of two white dwarfs. If a surviving companion or a dense circumstellar medium (CSM) from the progenitor's mass loss is detected, the origin of SD can be affirmed.

To date, no surviving companion has been unambiguously confirmed in the Milky Way. We have thus turned to the five young SNRs Ia in the Large Magellanic Cloud (LMC). We have used HST images to search for surviving companions in these SNRs. We have also used archival VLT MUSE spectra to search for stars with high radial velocities.

From these analyses, we found possible surviving companion candidates of SN progenitors within SNRs Ia outside the Milky Way. We have further used VLT MUSE spectra and HST Hα images of these SNRs to discover forbidden-line-emitting nebular knots with high density that most likely belong to a CSM. We was pleasantly surprised to find that bright forbidden line emission from dense CSM in four of five Type Ia LMC SNRs. The existence of CSM makes physical structures and environments of these SNRs appearing to be complex. The SD origin for SNe Ia could be more prevalent than previously thought.

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