The Dominance of the r-Process in Heavy Element Nucleosynthesis within Reticulum II Ultrafaint Dwarf Galaxies

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Abstract:- This study investigates the paramount role of the r-process in heavy element nucleosynthesis within the Reticulum II ultrafaint dwarf galaxies, shedding light on fundamental questions in classical astronomy. We explore the formation of galaxies, probing the influence of mass and density on heavy element creation. Conventionally, supernova explosions were attributed to heavy element formation, prompting us to conduct experiments to examine the feasibility of the r-process and its connection to heavy element abundance in Ret II Ultra-Faint Dwarf (UFDs) galaxies. Through comprehensive citation analysis, our research challenges the prevailing belief in supernovae as the primary mechanism for heavy element production in Reticulum II. Instead, our findings suggest that galaxy mergers and cloud mergers are the dominant drivers of this process. To support our conclusions, we collected data from three additional UFDs for comparative analysis alongside Reticulum II, employing structural and color-magnitude diagrams (CMD). This study conclusively establishes the r-process as the principal mechanism responsible for heavy element nucleosynthesis in Reticulum II, resulting in its elevated luminosity compared to other ultrafaint dwarf galaxies characterized by lower elemental abundances. The heavy elements generated during this process originate from neutron star mergers and r-process nuclear fusion reactions. Consequently, Reticulum II stands out as a unique, outstanding, and brighter ultrafaint dwarf galaxy, with the r-process exclusively governing its chemical reactions, while others predominantly rely on the S and P processes.

Keywords:- *r-process; heavy element nucleosynthesis; Reticulum II; ultrafaint dwarf galaxies; galaxy mergers*

I. INTRODUCTION

In 2016, the discovery of the diminutive and faint galaxy known as Reticulum II (Ret II) challenged the long-held belief that supernova explosions were the primary source of the universe's heaviest elements [1]. Instead, the chemical composition of the stars within Ret II strongly pointed towards neutron-star mergers as the mechanism responsible for generating elements such as gold and platinum [2].

Nevertheless, ultrafaint dwarf galaxies stand as the smallest, most dark-matter-dominated, and least chemically enriched stellar systems in the cosmos, offering critical insights into dark matter physics and the formation of galaxies on the smallest scales. Their unique characteristics blur the once-distinct boundary between the Milky Way's dwarf galactic satellites and its globular clusters, necessitating detailed measurements of velocity dispersion, metallicity, and metallicity dispersion to infer the presence of dark matter halos [3].

Recently, the Dark Energy Survey (DES) uncovered nine new Galactic satellites, with seven resembling typical ultrafaints. Among them, Ret II has emerged as a focal point of interest due to its proximity, flattened morphology, and potential gamma-ray emissions linked to dark matter annihilation [4].

This study seeks to unravel the enigmatic nature of the ultrafaint dwarf galaxy Reticulum II and ascertain the dominant role of the r-process in heavy element nucleosynthesis within it. While various hypotheses exist regarding the origin of Ret II, this research aims to consolidate the facts and hypotheses proposed by astronomers to elucidate the r-process's impact in Reticulum II.

Beyond its astronomical intrigue, understanding Ret II holds significance in addressing fundamental questions in galactic astronomy, shedding light on the universe's age and the roles played by celestial objects like ultrafaint dwarf galaxies. The primary objective is to discern the nucleosynthesis process responsible for the disparity in heavy element abundance between Ret II and other ultrafaint dwarfs. This entails identifying the types of ultrafaint dwarf galaxies and characterizing the predominance of heavy elements within them, with a specific focus on Ret II's role as a reservoir of heavy elements driven by the rapid neutron capture process (r-process).

Chapter 2 presents results from an initial spectroscopic exploration of individual stellar targets along the line of sight to Ret II, delving into the intricacies of the r-process, its associated reactions, and the formation of heavy elements. Furthermore, it investigates the process responsible for the lower heavy element levels observed in other ultrafaint dwarf galaxies. In Chapter 3, we detail the data acquisition methods, utilizing structural property parameters from four ultrafaint dwarf galaxies, including Ret II, and subsequently present and discuss our findings.

II. ULTRA-FAINT DWARF GALAXY

A. Introduction

A galaxy is a complex system comprising stars, stellar remnants, interstellar matter, dust, and dark matter, with the term "galaxy" originating from the Greek word "galaxias," meaning "milky," in reference to our own Milky Way. Galaxies span a vast size range, from dwarf galaxies containing just a few hundred million stars to giant galaxies hosting up to one hundred trillion stars, all orbiting the galaxy's center of mass [6]. Our understanding of galaxies, including their observations and definitions, primarily relies on their stellar constituents. Consequently, any theory regarding galaxy formation must address the processes leading to star formation, as well as the efficiency of converting gas clouds into stars, known as star formation efficiency (SFE) [7].

B. Dwarf Galaxy

Dwarf galaxies are compact stellar systems, typically composed of approximately 1,000 to several billion stars, in contrast to the Milky Way, which harbors 200 to 400 billion stars. Occasionally, galaxies like the Large Magellanic Cloud, with over 30 billion stars and a close orbit around the Milky Way, are classified as dwarf galaxies [8]. Dwarf galaxies encompass various subtypes, including dwarf elliptical galaxies (dE), dwarf irregular galaxies (dIrr), and Ultra-Faint Dwarfs (UFDs). Ultra-faint dwarfs, identified before 2005, possess absolute magnitudes brighter than their Plummer radii of 200 parsecs (pc), with central surface brightness exceptions like Sextans and Ursa Minor, which measure at 26 mag/arcsec [7]. Notable ultrafaint galaxies include Blue compact dwarfs, Ultra-compact dwarfs such as Reticulum II, Sagittarius II, Phoenix II, and Tucana III. Among these, Reticulum II stands out as an ancient Ultra-compact dwarf galaxy within the Local Group.

C. Reticulum II

The discovery of Reticulum II occurred in 2015 through the analysis of Dark Energy Survey images by DES Collaboration et al. [9]. Characterized by an elongated shape with an axis ratio of 0.6, its size exceeds that of typical globular clusters. Reticulum II boasts a magnitude of -2.7 and is situated at a distance of 30 kiloparsecs from Earth. Within this galaxy, blue horizontal branch stars are present, and notably, it exhibits an unusual enrichment of rapid neutron-capture process (r-process) elements.

In nuclear astrophysics, the r-process comprises a series of nuclear reactions, including fusion and fission, responsible for generating approximately half of the elements heavier than iron in the periodic table. The remaining heavy elements are produced by the proton (p)-process and slow (s)-process. Neutron capture during r-process nucleosynthesis leads to the formation of neutron-rich, weakly bound nuclei with low neutron separation energies. There are three primary candidate sites for r-process nucleosynthesis: low-mass supernovae, Type II supernovae, and neutron star mergers [4]. Elements beyond zinc are synthesized primarily through the rapid (r) and slow (s) neutron-capture processes. The debate over the primary production site for r-process elements, such as europium, has spanned six decades, with early studies suggesting continuous production in events like core-collapse supernovae. However, evidence from the local universe supports the notion that r-process production mainly occurs during rare occurrences, such as neutron star mergers. The presence of a europium abundance plateau in certain dwarf spheroidal galaxies has been proposed as evidence of infrequent r-process enrichment in the early Universe [9].

D. Rapid Neutron-Capture Process

The primary mechanism responsible for creating elements heavier than iron is the rapid neutron-capture process, which appears to primarily occur during neutron star mergers rather than supernova explosions. While hydrogen and most of the universe's helium were produced during the initial moments of the Big Bang, all other chemical elements, except for a small quantity of lithium, originated from stellar interiors, supernova explosions, and neutron star mergers. Elements up to iron are synthesized in the intense heat of short-lived massive stars, where nuclear fusion generates increasingly heavier elements, powering the star's radiance. Elements heavier than iron, constituting the majority of the periodic table, predominantly form in environments with neutron densities exceeding one million particles per cubic centimeter. These free neutrons, when captured by seed nuclei, lead to the creation of heavier, radioactive nuclei, which subsequently decay into stable heavy elements. This process, known as the slow neutron capture process (s-process), primarily occurs during the later stages of stars with masses ranging from 1 to 10 solar masses ($M_\odot$). However, the s-process accounts for only approximately half of the isotopes beyond iron. The mergers of orbiting neutron stars, on the other hand, meet the criteria for the production of r-process nuclei. The heavy elements formed during neutron star mergers through the r-process reaction contribute to the higher luminosity of stars in Reticulum II, rendering it unique, exceptional, and brighter than other ultrafaint dwarf galaxies [12].

E. Formation of Heavy Elements

As free neutrons are captured by seed nuclei, they give rise to heavier elements [8]. Highly r-process-enhanced metal-poor stars have been identified in ultrafaint dwarf (UFD) galaxies, including Reticulum II. The presence of such stars in only a few UFDs suggests that the r-process site may involve exceedingly rare but prolific events, such as neutron star mergers (NSMs) [14]. Given the relatively short star formation history of UFDs, it remains a puzzle how they could have experienced such infrequent phenomena. Cosmological hydrodynamic zoom-in simulations were conducted to elucidate the formation of Ret II stars in UFDs, employing a simple model for NSMs consistent with observational data, including NSM rates and europium (Eu) masses. These simulations revealed that only one galaxy in a volume hosting 30 UFD analogs exhibited abundances akin to Ret II, emphasizing the rarity of such abundances [15]. Key parameters, including the rapid formation of subsequent stars from r-process-enriched gas, were explored to determine their influence on the formation of Ret II stars in UFDs [16]. It was subsequently established that the initial and subsequent bursts of Ret II stars require approximately 10 to 100 light years to form. Detailed investigations of Ret I and Ret II stars, conducted using ground- and space-based telescopes, have provided valuable insights into the origin of the astrophysical r-process. Notably, the overall abundance patterns of r-process elements in Ret I and Ret II stars closely resemble that of the solar system, despite differences in the gas composition of their formation environments. These stars, typically characterized by low metallicities ([Fe/H]), ranging from -1.5 to as low as -3.5, formed early in cosmic history, while the solar system is relatively young at 4.6 billion years. The congruence in abundance patterns between such disparate systems underscores the robust behavior of the r-process [17]. Additionally, r-process nucleosynthesis models derived from accelerator-generated data must align with constraints derived from astronomical observations of heavy element abundances in the universe. Fortunately, chemically primitive stars scattered throughout the galaxy, characterized by high levels of r-process elements, provide a valuable natural laboratory for.

III. METHODOLOGY

In conducting this study, we adopted a comprehensive approach that involved reviewing existing research on Reticulum II (Ret II) and ultrafaint dwarf galaxies (UFDs) while also gathering data from various sources, primarily utilizing the Visual Catalog, an astronomical database application. The methodology employed for data analysis drew inspiration from the work of [17], whose M2FS experimental data analysis provided valuable insights into Ret II.

A. Data Collection and Sources

Our initial step involved reviewing the literature and works of other researchers focused on Ret II and UFDs. We sourced astronomical data primarily through the Visual Catalog application, which consolidates astronomical research findings and cataloged data.

B. Data Analysis and Instrumentation

To delve into the specific observations of Ret II, we leveraged the research conducted by [17], who carried out observations of Ret II using the Michigan/Magellan Fiber System (M2FS) on the 6.5-meter Magellan/Clay Telescope situated at the Las Campanas Observatory in Chile. The M2FS employs a configuration featuring 256 optical fibers, each equipped with an entrance aperture of 1.2 arcseconds in diameter and a focal surface spanning 29 arcminutes in diameter. This configuration allows for versatile spectroscopic modes, and for the Ret II observations, both M2FS spectrographs were identically configured in High Resistivity mode, incorporating order isolation filters to cover the wavelength range from 5132 to 5186 Å with an effective resolution of R 18000.

C. Structural Properties Analysis

In addition to Ret II, we extended our analysis to encompass four ultrafaint dwarf galaxies: Sagittarius II (Sgr II), Phoenix II (Phe II), Ret II, and Tucana III (Tuc III). Our data collection included crucial structural parameters for each of these ultrafaint dwarf galaxies, such as mass, absolute magnitude, ellipticity, and position angle.

D. Observational Details

Observations of the Ret II field were conducted for a total duration of 2 hours. Notably, the field's positioning in the western sky during evening twilight led to an increase in air mass, ranging from 1.3 to 1.7, throughout our observation period.

E. Data Processing

To ensure the reliability of our data, we initiated data processing by conducting over-scan, bias, and dark current corrections. Subsequently, we performed an averaging process on three individual exposures, resulting in the creation of a single, stacked science frame for each of the two spectrographs. For the precise determination of wavelength solutions, we employed a fourth-order cubic SP line fitting procedure, referencing 30 emission lines identified in the identically extracted arc spectrum from the same aperture. Variations in fiber throughout were accounted for by normalizing each spectrum using a fit to the continuum in the twilight spectrum, obtained from the same aperture, following the methodology outlined in [17].

IV. RESULT

Table 1 presents a summary of the structural properties for four ultrafaint dwarf galaxies: Sagittarius II (Sgr II), Phoenix II (Phe II), Reticulum II (Ret II), and Tucana III (Tuc III). The analyzed parameters encompass a range of critical characteristics, including Absolute Magnitude, Mass, Distance, Ellipticity, Angular Position, and Color Magnitude. Distance measurements are crucial for understanding the spatial relationships between UFDs and their respective metallicities within various globular clusters.

Table 1: Structural Properties of Ultrafaint Dwarf Galaxies: (Srg II, Ret II, Phe II and Tuc II)

Parameter	Sgr II	Ret II	Phe II	Tuc II
m – M (mag)	19.2±0.1	17.5±0.1	19.6±0.1	16.8±0.1
E(B-V)	11.0	0.002	0.01	0.01
Distance (kpc)	70.1±2.3	31.5±1.3	84.3±4.0	22.9±0.7
Mv	-5.2±0.1	-3.1 ± 0.1	-27±0.4	-1.3±0.2
Ellipticity	< 0.1	0.6 ±0.1	0.4±0.1	0.2±0.1
Position Angle (deg)	Unconstrained	68 ± 2	156±13	25±38

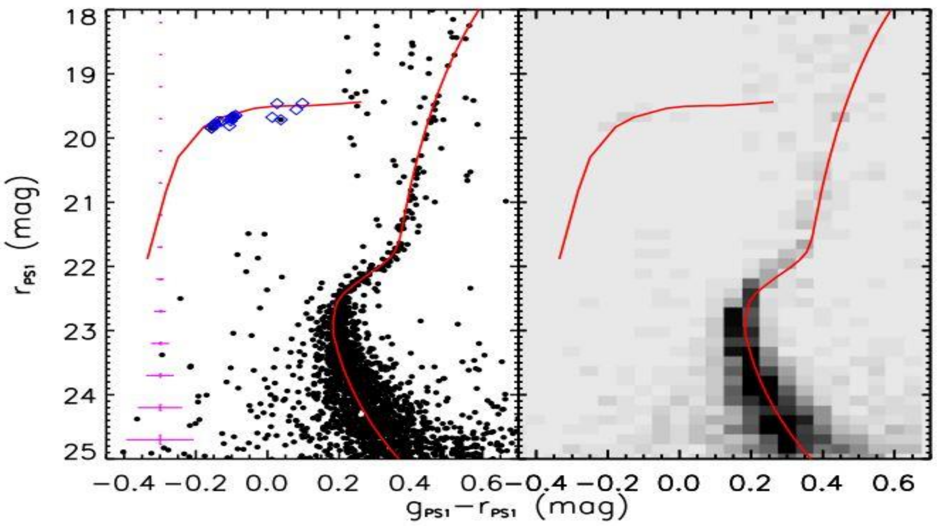

Fig. 1: Left: Color-Magnitude Diagram (CMD) of Sagittarius II (Sgr II), encompassing stars located within one half-light radius of its central region. Magenta error bars represent the uncertainties in both color and magnitude, with respect to the r magnitude. Right: A background-subtracted binned Hess diagram for Sgr II, focusing on the same region highlighted in the left panel. A red line superimposed on the diagram represents the PS1 fiducial for M15 [18] [19].

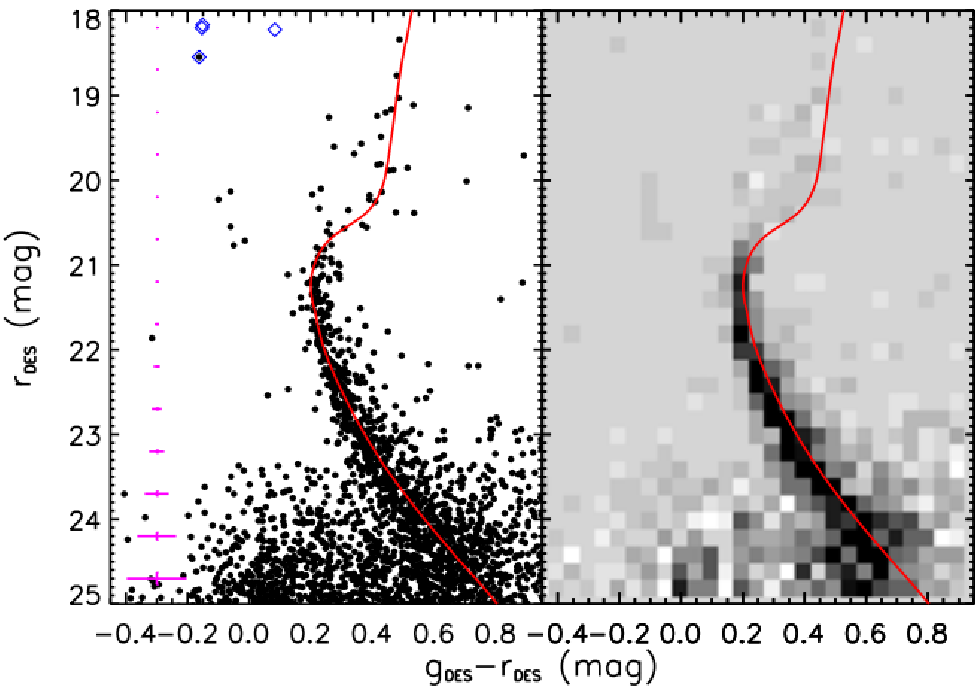

Fig. 2: a. Color-Magnitude Diagrams (CMDs) and Hess diagrams of Reticulum II (Ret II), illustrating stars within one half-light radius of its central region. Magenta error bars represent color and magnitude uncertainties, varying with the r magnitude. Blue open diamonds denote blue Horizontal Branch (HB) candidates observed within our Field of View (FoV). Overlaid on the CMDs is a red line, indicating a metal-poor Dartmouth isochrone with an age of 13.5 billion years: [Fe/H] = −2.4 for Ret II. b. CMDs and Hess diagrams of Phoenix II (Phe II), comprising stars situated within one half-light radius of its central region. Similar to panel a, the magenta error bars illustrate color and magnitude uncertainties linked to the r magnitude. Blue open diamonds represent blue Horizontal Branch (HB) candidates within our Field of View (FoV). The red line corresponds to a metal-poor Dartmouth isochrone with an age of 13.5 billion years: [Fe/H] = −2.2 for Phe II. c. CMDs and Hess diagrams of Tucana III (Tuc III), encompassing stars located within one half-light radius of its central region. As in the previous panels, magenta error bars denote color and magnitude uncertainties associated with the r magnitude. Blue open diamonds signify blue Horizontal Branch (HB) candidates observed within our Field of View (FoV). Overplotted on the CMDs is a red line, indicating a metal-poor Dartmouth isochrone with an age of 13.5 billion years: [Fe/H] = −2.4 for Tuc III [20].

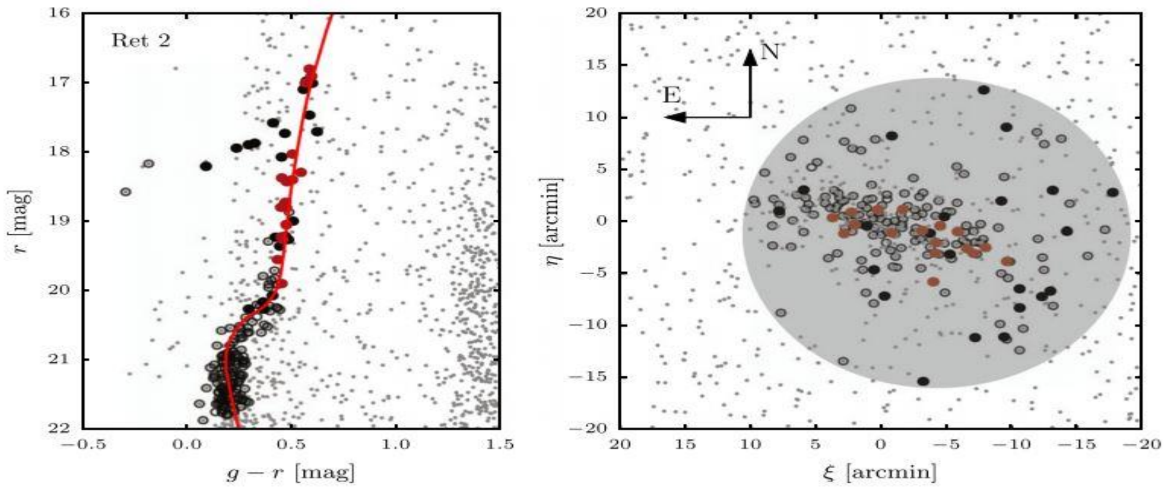

Fig. 3: Magellan/M2FS Spectroscopy of Reticulum II.

Left: Color-Magnitude Diagram (CMD) illustrating stars within Reticulum II (Ret II) located at R ⩽ 15 arcminutes of its center [21]. The red line represents the Dartmouth isochrone with parameters: age = 12 Gyr, [Fe/H] = -2.5, [α/Fe] = +0.4, and m - M = 17.4 (Dotter et al. 2008). Large circles encompass stars identified as potential Ret II members by the DES MW working group (J. Simon 2015, private communication) and subsequently selected for M2FS spectroscopic targeting. Filled circles highlight 37 stars meeting quality-control criteria for spectroscopic measurements. Among them, red circles denote stars whose spectroscopic characteristics align with Ret II membership, while black circles indicate spectroscopic nonmembers. Right: Standard coordinates for stars within 0.2 magnitudes of the isochrone displayed in the left-hand panel. The markers maintain consistent meanings as in the left-hand panel. The large shaded circle represents the field of view for the Magellan/M2FS instrument [22].

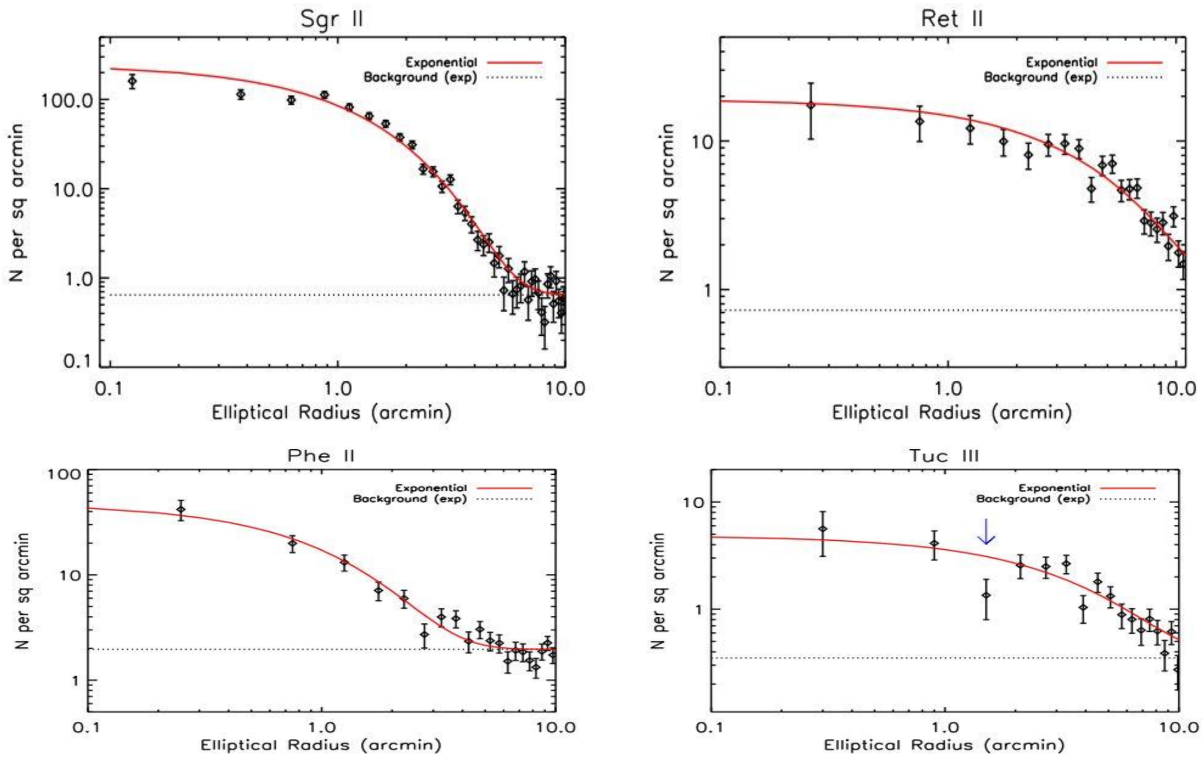

Fig. 4: Color-Magnitude Diagrams (CMD) and Stellar Profiles

This figure presents Color-Magnitude Diagrams (CMDs) for Sagittarius II (Sgr II), Reticulum II (Ret II), Phoenix II (Phe II), and Tucana III (Tuc III). The stellar profiles of these ultrafaint dwarf galaxies are also depicted. The red and dotted lines within each profile represent the best-fit 1D exponential and the background surface density, respectively. Notably, in the case of Tuc III, a blue arrow draws attention to a bin where the presence of two bright stars causes a noticeable dip in the profile. It is important to highlight that our profile fits are derived from the 2D distribution of stars, offering a more comprehensive perspective than traditional 1D profile analysis [20].

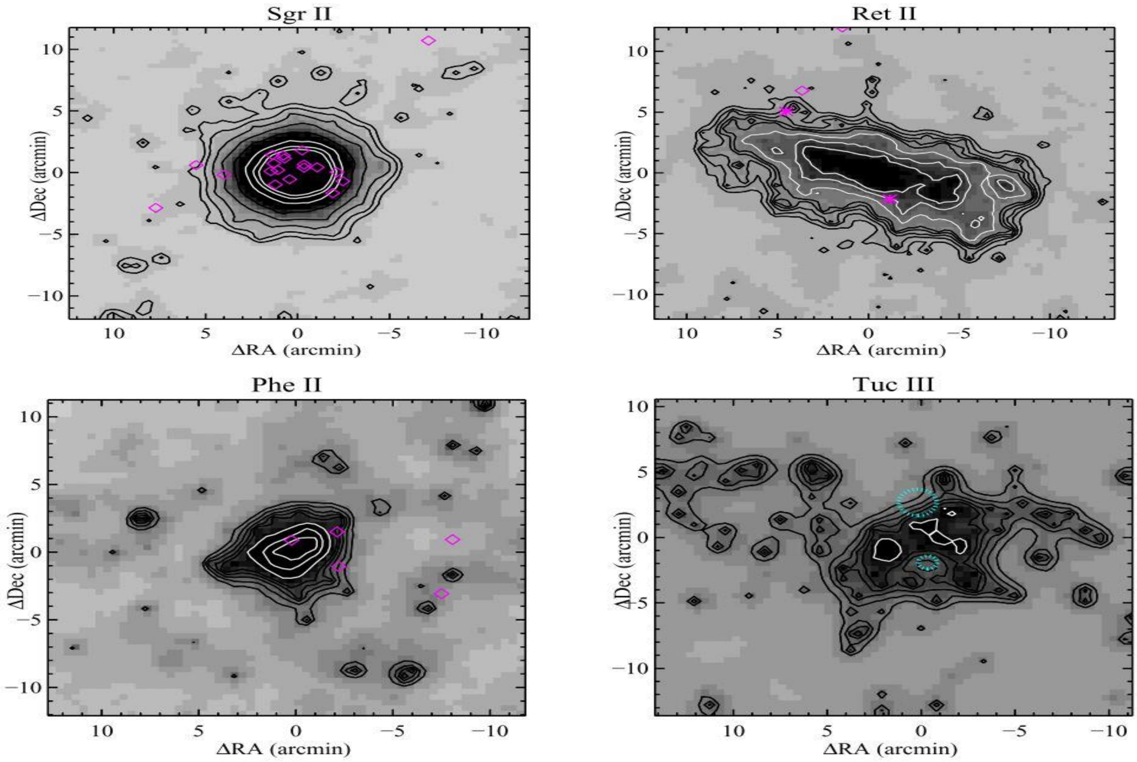

Fig. 5: Structural Color-Magnitude Diagram (CMD) and Smoothed Matched-Filter Maps of Satellites

This figure showcases a Structural Color-Magnitude Diagram (CMD) for Sagittarius II (Sgr II), Reticulum II (Ret II), Phoenix II (Phe II), and Tucana III (Tuc III), along with smoothed matched-filter maps of these satellite galaxies. The contour levels for Sgr II are depicted at the 3σ, 5σ, 10σ, 20σ, 40σ, 80σ, 120σ, and 150σ levels above the modal value. For the other satellite galaxies, the contour levels correspond to the 3σ, 4σ, 5σ, 6σ, 7σ, 10σ, 15σ, and 20σ levels. Magenta diamonds represent likely blue Horizontal Branch (HB) stars. In the Tuc III map, cyan circles draw attention to the presence of bright stars, leading to stellar incompleteness at those specific positions [20].

V. DISCUSSION

In this section, we delve into the analysis of four distinct ultrafaint dwarf galaxies: Sgr II, Ret II, Phe II, and Tuc III, utilizing their structural and color-magnitude diagrams (CMDs). The CMDs for Sgr II, Ret II, Phe II, and Tuc III, featured in Figure 1, encompass stars situated within one half-light radius of their respective centers. Magenta error bars have been included to represent the mean photometric errors determined through artificial star simulations, with the error bars displayed in an arbitrary color for ease of reference. Blue open diamonds in these diagrams signify the selection of blue Horizontal Branch (HB) star candidates, chosen within a color range of < 0.2 and a magnitude span of 0.5, centered on the HB sequence of a metal-poor star.

A. SGR II:

The table provides various parameters, such as m – M (mag), E(B-V), distance (kpc), absolute magnitude (Mv), ellipticity, and position angle, for Sgr II. A negative m – M (mag) value suggests that Sgr II has a rounded form. A low E(B-V) value of E(B-V) = 0.002 indicates that Sgr II appears less luminous. The distance of 70.1 ± 2.3 kpc places Sgr II relatively farther from its constellation's clouds, contributing to its low luminosity. With an absolute magnitude Mv, Sgr II exhibits a lower brightness due to its lower mass. An ellipticity value of 0.5 illustrates Sgr II as an ellipse in shape, while a position angle without constraints suggests its unrestricted orientation within its constellation. Figure 1 presents deep photometry results for Sgr II, revealing a well-defined main sequence turnoff (MSTO) and several blue HB candidates concentrated around the center of Sgr II. This CMD indicates an old stellar population with Fe/H.

B. RET II:

Table 1 showcases parameters for Ret II, including m – M (mag), E(B-V), distance, Mv, ellipticity, and position angle. A positive m – M (mag) value implies that Ret II has an elongated form, while E(B-V) = 0.002 signifies its relatively low luminosity. The distance measurement indicates that Ret II is closer to the clouds of its constellation, resulting in higher luminosity when observed with the 6.5-M Magellan/Clay Telescope. An Mv value of 1 suggests that Ret II is bright due to its higher mass. An ellipticity of 0.6 ± 0.1 confirms Ret II as an ellipse in shape, and a position angle of 68 ± 2 imposes constraints on its orientation. In Figure 2, Ret II's CMD exhibits a well-defined main sequence and blue HB candidates, while density contours trace these features. The structural parameters, including rhpc and absolute magnitude, indicate that Ret II is elongated and falls in the luminosity range of 0.6 value. Despite its elongation, no clear signs of tidal features are evident in the density map. Spectroscopic analysis confirms Ret II's status as an ultrafaint dwarf galaxy, characterized by its velocity and metallicity.

C. PHE II:

Table 1 provides parameters for Phe II, including m – M (mag), E(B-V), distance, Mv, ellipticity, and position angle. A positive m – M (mag) value implies that Phe II has a rounded form, while E(B-V) = 0.01 suggests its relatively low luminosity. An ellipticity value indicates that Phe II has an elliptical shape, and a constrained position angle specifies its orientation. In Figure 1, Phe II's CMD reveals clear features, including a sparsely populated RGB and potential blue HBs. Tentative signs of extended structure are visible in the density map, particularly in the southeast direction. Structural parameters suggest Phe II as a dwarf galaxy with low luminosity.

D. TUC III:

Table 1 presents parameters for Tuc III, including m – M (mag), E(B-V), distance, Mv, ellipticity, and position angle. A positive m – M (mag) value indicates that Tuc III has a rounded form, while E(B-V) = 0.01 suggests its relatively low luminosity compared to Ret II. The absolute magnitude Mv implies that Tuc III is bright due to its higher mass but lower than Ret II. An ellipticity value confirms Tuc III as an ellipse in shape, and a constrained position angle specifies its orientation. Figure 1 showcases Tuc III's CMD, featuring a narrow main sequence consistent with old, metal-poor stellar populations. Absence of HB candidates within the Magellan photometric catalog is noted. In Figure 4, 1D stellar radial profiles are presented, and our best-fit exponential profile, derived from the 2D stellar distribution, is overlaid. Stellar incompleteness, indicated by a blue arrow, results from two bright stars. The radial density profiles of Ret II and Tuc III do not reach the background level, limiting the investigation of their outer regions. In Figure 5, Tuc III's stellar stream presence and bright stars throughout complicate the estimation of its structural parameters.

VI. CONCLUSIONS

The analysis of Reticulum II (Ret II) reveals a fascinating celestial object with characteristics resembling both globular clusters and ultrafaint dwarf galaxies. Key findings and conclusions from this study are summarized below:

- **Nature of Ret II:** Ret II's size and luminosity place it in a category between globular clusters and ultrafaint dwarf galaxies. While it shares some properties with both, its dynamic and structural characteristics align more closely with those of dwarf galaxies. Thus, based on these characteristics, it is concluded that Ret II is indeed an ultrafaint dwarf galaxy.
- **Dynamical Mass-to-Light Ratio:** Under the assumptions of dynamic equilibrium and minimal contamination from binary stars, Ret II exhibits a strikingly high dynamical mass-to-light ratio of approximately 462 ± 264 - 157 M/L. This ratio is one of the largest ever inferred for any known astronomical object. However, it is essential to recognize the potential uncertainties associated with these assumptions, which may affect the validity of this conclusion.
- **Heavy Element Enrichment:** Ret II stands out due to its relatively massive size and luminosity compared to other ultrafaint dwarf galaxies. This brightness can be attributed to the presence of heavy elements, specifically those heavier than iron, which result from nucleosynthesis processes. In particular, the rapid neutron capture process (r-process) is responsible for synthesizing these neutron-rich heavy isotopes in the cores of dying massive stars.
- **Significance of the r-Process:** The r-process is crucial for producing the most neutron-rich stable isotopes of heavy elements. Typically, it can synthesize the heaviest four isotopes of each heavy element. Ret II serves as a valuable astronomical laboratory for studying early r-process enrichment. The insights gained from Ret II contribute to our understanding of r-process mechanisms and complement measurements in other dwarf galaxies.
- **Neutron Star Mergers:** While core-collapse supernovae were initially considered as potential sites for r-process nucleosynthesis, growing evidence suggests that r-process production primarily occurs during rare events, such as neutron star mergers. This finding has significant implications for our comprehension of heavy element formation in the universe.

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