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International Research and Evaluations in the Field of Astrophysics

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INTERNATIONAL RESEARCH AND EVALUATIONS IN THE FIELD OF ASTROPHYSICS

EDITOR

DOÇ. DR. EBRU AKTEKİN ÇALIŞKAN

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CONTENTS

Chapter 1

WHITE-DWARF X-RAY BINARIES: FROM DISCOVERY TO MODERN UNDERSTANDING

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Introduction:

The x-ray emitting white dwarf binaries, most often dubbed “cataclysmic variables” are among the first “exotic” phases in stellar evolution pathways to have been discovered. In the earliest historical accounts of astronomical observations, some of these systems, Guest stars were mentioned. These stars were, for the most part, invisible to the naked eye, but they showed brightening and reappearance sometimes with some degree of periodicity. The nature of such objects stayed a mystery for the most part until advanced observational techniques and a basis of knowledge of astrophysics were acquired.

After the classical period, with the advent of imaging and photometry, detailed observation of novae started to be conducted. As astronomers started to track variable stars and their light curves, novae were observed too. Mid-19th century brought the Nova Ophiuchi 1848’s light curve, showing these objects were still there after periods of high intensity outbursts, the stars remained.

The discovery of recurrent novae further solidified the understanding that these events were not life-ending or transformative events for the progenitors, unlike supernovae.

In 1939, Laughlin categorised novae according to light curve properties, most importantly the speed of evolution after the initial intensifying in brightness. He categorised the novae as slow and fast novae. M. F. Walker’s 1954 observation revealed the close binary nature of these systems, comprising of a late-type star and a compact post-stellar evolution object, giving astrophysicists a starting point to work on.

Then in the ‘70s came the closer observations of dwarf novae, showing these systems undergo complex thermodynamic and hydrodynamic interactions, and their outbursts aren’t due to large runaway fusion events causing mass loss in the shape of a shell ejection like “classical novae”.

The astrophysicists then started building mass transfer models for cataclysmic variables. The observed phases of the hotspots were matched with mass flow-accretion disk interactions, and more detailed analyses

were subsequently done using computational simulations. (Smak 1971) (Warner, Peters, 1972) (Armitage, Livio, 1996)

Also the polarisation characteristics of the light emitted by some of these compact objects resulted in the discovery of a highly magnetised type of cataclysmic variables: Polars. These stars were shown to also emit non-thermally, and their existence was proved via direct x-ray imaging thanks to ROSAT's X-Ray surveys.(Tapia, 1977) (Beuermann, 1999)

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The first observation of a "Nova" was made by Tycho Brahe in the 16th century. It was recorded in the constellation Cassiopeia and was recorded as "De Nova Stella" (… new star).

The novae discovered in this early period were almost always supernovae due to the immense power of such events. There have been only 6 nova events discovered until 1887, with the brightest being 1670-discovered Nova Vulpecula, reaching magnitude 2.7, making it easily visible as a new star, while other events have been fainter than magnitude 3.

Telescopes becoming commonplace, especially past the mid-18th century, allowed the observations of novae after outbursts. Nova Ophiuchi 1848 dimmed down to magnitude 13.5 after several years, demonstrating that these outbursts did not destroy the progenitor.

Observations in the early 20th century suggested a significant difference in power for different types of such events, and with it novae which weren't supernovae were called "classical novae". Especially with the first observations of repeating novae, like Nova Corona Borealis 1866, repeating in 1946, novae have been understood to be repeating, cataclysmic events, unlike supernovae, which destroy the progenitor and create a remnant unlike it. Virtually all novae are believed to be recurrent now. (Murdin, 2001)

Merle F. Walker's 1954 publication about Nova DQ Herculis 1934 shed light to the true nature of cataclysmic variables. Using a 100-inch reflector(Roughly the size of the soon-to-retire HST) Walker observed

the DQ Herculis system to be a very-short period binary: The primary eclipse is 0.9 magnitude deep, and the secondary eclipse is too small to be observed. The smaller companion is observed to be bluer, implying greater surface temperature. The period of this binary was observed to be 4 hours and 39 minutes. The light curve generated implied that the smaller component of DQ Herculis is a very dense, small object. Walker raised questions about the evolution of such systems, which took some decades to be answered. (M.F.Walker, 1954)

McLaughlin in 1939 did a review to classify light curves of novae. These novae were classified by their “fastness”. McLaughlin observed the total rise in magnitude to be about 11 magnitudes. The novae would stop increasing in brightness for a short while, marked in the work as Pre-Maximum halt, which ranged from a couple of hours to 40 days, which happened at 1-2 magnitudes below the maximum intensity observed. Fast novae were observed to take the same time up to reach the maximum as the duration o the initial rise from 9-10 magnitudes below, but this period was longer for slow novae.

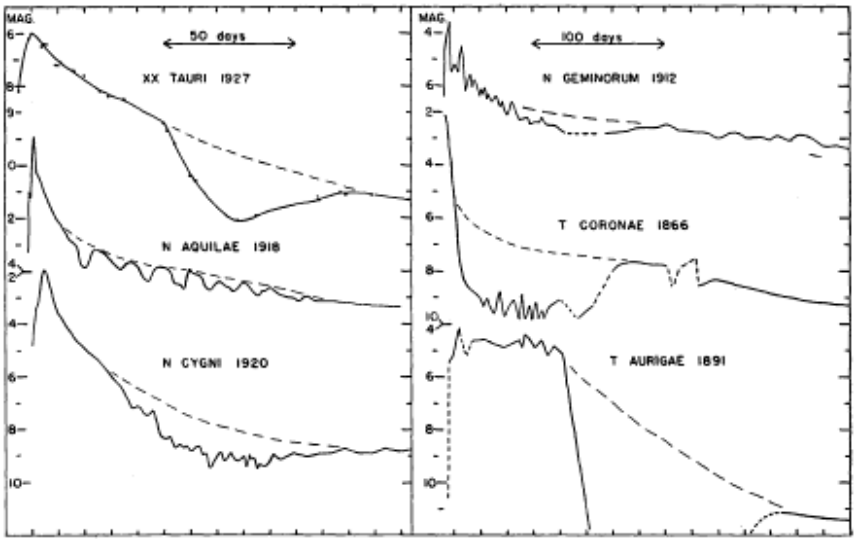

Figure 1: Light curves of novae of different speed types from the 1939 paper of McLaughlin.

In the work, McLaughlin confirms some “repeating novae” and suggests new ones, such as Nova Sagittarii 1919.

1974 paper of Warner on “Rapid Blue Variables” noted the observations on Z Cha, a dwarf nova, which is also a very-short period eclipsing binary(107m). The authors have made photometric observations during both the quiescent phase and the outburst phase of the system. In a 1972 paper, Warner and Robinson observed oscillations of 16-34 second periods. In Z Cha’s observation during the outburst, a 20-inch reflector was used without filtering for photometry. The energy output of the dwarf nova was observed to be 10^39 erg, which is 6 orders of magnitude smaller than the gravitational binding energy of the system, meaning likely no mass loss as shell-like classical novae happen with these dwarf nova outbursts.

In 1976, a close white-dwarf binary, AM Herculis was observed to have a peculiar property. In Tapia’s observation, the light from this system was both linearly and circularly polarised. Using SAS-3, a soft X-ray emission was observed from this system’s position. The system was observed to have a period of 3.1 hours. The phase of linear and circular polarisation pointed to the source of both polarisations being the same object. The strength of this polarisation and the frequency dependence of it strongly suggest the existence of cyclotron radiation of electrons in a field with roughly 2*10^8 Gauss strength. At the time of this paper, main-sequence stars were known not to possess magnetic fields stronger than 10^7 Gauss, so this magnetisation was attributed to the white dwarf companion. From broadband photometry, the ultraviolet radiation was observed to be unpolarised, implying the blue source was unaffected by the magnetic field and was likely thermal. Using theoretical calculations, the authors then estimate the radius of the x-ray source to be between 2*10^7 to 2*10^8 cm, which was known to be the size of a white dwarf star.

Patterson and Raymond (1985) observe accreting white-dwarf systems with different accretion rates in HeII lines at 468.6nm and 164.0nm. These ionised lines are expected to be by-products of Extreme UV and Soft X-ray emission from the boundary layer, using an optically thick boundary layer model. Above 10^17 g/s, they note significant soft X-ray

emissions. The theoretical models seem to agree above this mass cut-off, but the authors argue for the necessity for another photon source around 0.5keV.

With the commissioning of ROSAT, the X-ray observation capability increased significantly. ROSAT contained four instruments:

- XRT: The main X-ray imaging instrument, sensitive to soft X-rays.
- PSPC: Two proportional counters with positional and spectral resolution.
- HRI: Is a high-resolution crossed grid detector for imaging.
- WFC: Is an extreme UV telescope, sensitive between 6-30nm.

After ROSAT's XUV and X-ray catalogues, cataclysmic variables with strong magnetic fields started to be readily discovered. While polars were known/predicted from previous studies, ROSAT enabled the discovery of the intermediate polars.

XMM-Newton further improved such capabilities. It helped researchers draw the line between different CVs more easily and review some previously done work. One such example is V1432 Aquilae: From ROSAT observations, this object was classified as a polar. A 2003 paper by Singh and Rana recommends reviewing the tag given. XMM-Newton's orbital characteristics allowed it to do a much longer observation of the system compared to ROSAT, to get a higher resolution power spectrum from its light curve and settle the classification debate.

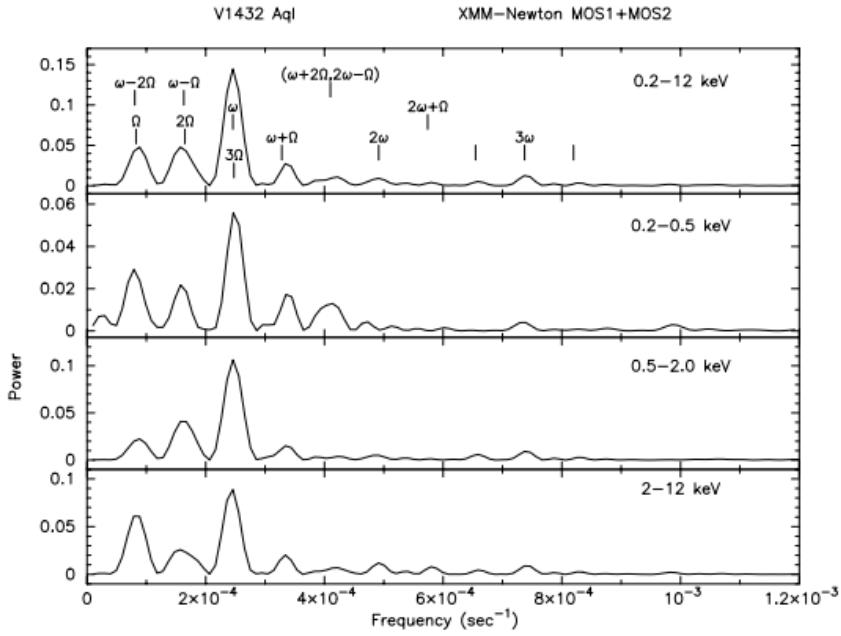

Figure 2: Power spectrum of V1432 Aquilae at combined, soft, medium, and hard X-ray bands. (Singh & Rana, 2003)

XMM-Newton observed this system for nearly two full orbits, raw light curves were then converted to power spectra using Discrete Fourier Transformation, in which the spin of the white dwarf is hypothesised to be 4070s, and the orbital period 12116.3s, if true, combined with the x-ray spectrum would imply this system is more likely to be an intermediate polar.

The Theoretical Understanding of the Inner Workings of These "Stars"

How do White Dwarfs Generate X-Rays?

Most of the X-ray emission of white dwarfs is of thermal origin. When the stream of matter impacts the white dwarf, the plasma has an immense amount of kinetic energy, it is almost fully ionised, and thermal bremsstrahlung radiation is the dominant mode of emission. Lower than

1keV of kT needs to be achieved to enable line emissions. For non-magnetic accreting white dwarf stars, the accretion disk is not expected to be hot enough for X-ray emission. The emission is expected to originate from the boundary layer, especially as bremsstrahlung if the boundary layer is optically thin.

About half of the gravitational potential is converted into heat in the boundary layer, in which it is expected to be thermal x-ray emission. An optically thick boundary layer model was also created, which has good predictive power for high accretion rate white dwarf stars. (Patterson, Raymond, 1985)

Accretion Models:

1972 paper from Warner and Peters attempts to explain the accretion behaviour for the cataclysmic variables and semi-detached binaries using classical mechanical calculations. Using some symmetry arguments, they try to compute a flow path from the first Lagrange point, which is the intersection point of both objects' Roche lobes.

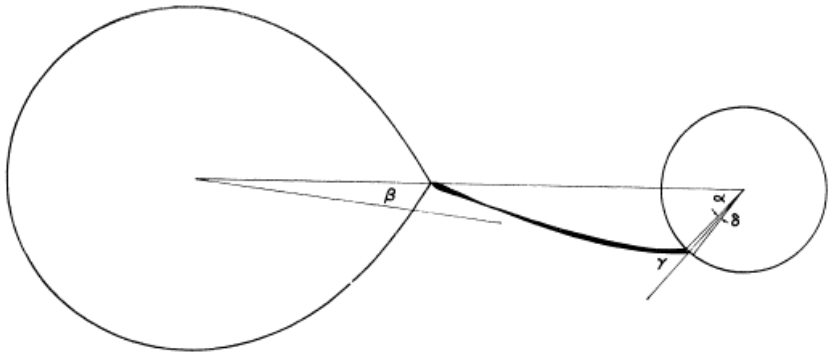

Figure 3: An approximate model of the mass transfer from the secondary to the CV primary. (Warner & Peters, 1972)

The particles are assumed to leave L1 at thermal velocities of the secondary star. Then the restricted three-body problem is solved for these particles, which give out the angles specified in the figure. The results obtained conflict with the analyses done by Smak (1971), but authors

note that for U Gem, this theoretical calculation is in good agreement with the observed hot spot parameters.

Armitage and Livio improve upon this model using computational methods. The gas stream from L1's collision with the accretion disk was modelled using Smooth Particle Hydrodynamics models. From the simulations, they conclude that a large amount of inflowing matter can skip off the impact point and compress to a smaller radius.

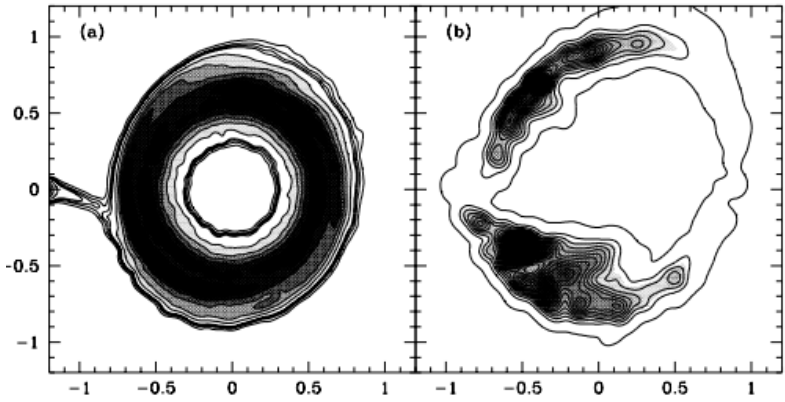

Figure 4: Eclipse and z= 0.15 density cross-sections of the simulated accretion disk, showing the lack of an axisymmetric distribution off-equator. (Armitage & Livio, 1996)

The authors argue this overflow behaviour is the reason why at phase 0.8 there is an observed increase in absorption density, which is explained by this behaviour causing increased column density.

This accretion geometry is, of course, a function of the magnetic field strength of the accreting primary. Beuermann (1999) divides such systems into three groups:

- Weak-field systems: The Magnetic field is "crushed", and accretion happens along the stellar equator.
- Intermediate-field strength: Magnetic field may survive the plasma pressure, causing a breaking-up of the accretion disk, the broken-up disk reaches the surface near poles, and emits X-rays

with a rotation period of the primary; such systems are called Intermediate polars.

- Strong fields: orbital and rotational periods are synchronised via expected magnetostatic interactions between the primary and the secondary objects. These systems do not develop accretion disks, and the material from L1 heads directly flows to the polar regions.

Both the accretion and the emission properties of accreting white dwarfs depend strongly on the magnetisation of the system.

Discussion:

Cataclysmic variables, while not as strong of an X-ray source as neutron stars, are a source of DC-to-daylight -and far beyond- emittance. These systems consist of secondaries filling out their Roche lobe and losing mass tidally to an electron-degenerate white dwarf star, and in this process, the gravitational potential is converted to kinetic and thermal energy and photons across the spectrum are emitted, mostly thermally, and via cyclotron radiation in some highly magnetised cataclysmic variables. Before the ability of direct observation of these systems, the initial categorisation was done through the intensity and the periodicity of outbursts occurring due to runaway thermonuclear processes as the accreted material reached critical thresholds. Then these stars were observed via secondary effects of X-ray production, and lower energy thermal effects, and by the mid-1980s onward, the development of highly precise X-ray telescopes like XMM-Newton and ROSAT broadened our understanding of these low-mass accreting systems via enabling direct X-ray measurements of these objects.

I thank Yüksel Ratip, one of my undergraduate students, for his help during the writing process of this manuscript.

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Chapter 2

THE MILKY WAY GALAXY

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1. Introduction

The Milky Way Galaxy is a collection of stars that includes the Solar System. It got its name because it appears as a pale, white stripe in the sky when viewed from Earth, as if milk had been spilt. Throughout history, people have wondered about the nature of the Milky Way, and even ancient philosophers have suggested that this stripe could be made up of stars. For example, in the 5th century BC, Democritus predicted that the Milky Way was made up of distant stars, but thinkers such as Aristotle opposed this view [1]. The true structure of the Milky Way began to be understood only after the invention of the telescope. When Galileo Galilei looked at the Milky Way with his telescope in 1610, he observed that this stripe was made up of countless faint stars, and he reported this in his work Sidereus Nuncius [1]. This discovery refuted Aristotle's view by showing that the Milky Way was not a "milky-white cloud" but a gigantic cluster of stars. In the 18th century, Thomas Wright (1750) and Immanuel Kant (1755) theorised that the Milky Way was made up of stars in a disk shape and that there might be other galaxies like the Milky Way, called "island universes" [1]. William Herschel attempted to create the first three-dimensional map of the Milky Way using star counts in different directions in his systematic telescope observations in the 1780s. Herschel depicted the galaxy as a flat disk with the Sun at its centre. However, Herschel realised that the star density was greater in one direction and thought that the galactic centre could be found in that direction [1]. However, due to the knowledge of the time, he did not know that interstellar dust absorbs light; therefore, he positioned the Sun more centrally than it actually is. In the early 19th century, great progress was made in determining the true size of the Milky Way and the location of the Sun. In 1918, Harlow Shapley studied globular clusters of stars and showed that their distribution in the sky was asymmetrical in the

direction of the constellation Sagittarius. Taking the centre of the globular clusters as the centre of the Milky Way, Shapley calculated that the diameter of the galaxy could be more than 100 thousand light-years and that the Sun was about 50 thousand light-years away from the centre [1]. Thus, he scientifically demonstrated that the Sun was not the centre of the galaxy. This result contradicted Jacobus Kapteyn's previous model of small, sun-centred galaxies. In the famous Shapley–Curtis debate of 1920, Shapley argued that the Milky Way was large enough to contain the entire universe, while Heber Curtis argued that the Milky Way was smaller and that other "spiral nebulae" (such as Andromeda) could be separate galaxies. Shortly thereafter, Edwin Hubble discovered Cepheid variables in the Andromeda "nebula" in 1924, proving that this object was millions of light-years away from the Milky Way. It was understood that Andromeda and similar "spiral nebulae" were independent galaxies like the Milky Way [1]. This discovery was a turning point in astronomy, showing that the Milky Way was just one of countless galaxies in the universe. Today, the structure and general features of the Milky Way are understood in great detail. The Milky Way is a barred spiral galaxy (type SBbc according to the Hubble classification) with a diameter of about 100,000 light-years [2]. It consists of a thin disk of stars filled with dust and gas, a thick bulge in the centre (galactic nucleus), and a spherical halo around it. The thickness of the galactic disk is about 1,000 light-years, and the central bulge has a radius of ~5,000 light-years [2][3]. The number of stars in the Milky Way is estimated to be around 200 billion, with some estimates indicating that this number could be as high as 400 billion [2]. The total mass of the galaxy has been measured to be about 1.5 trillion times the mass of the Sun; most of this mass is in the form of invisible dark matter [2]. The Sun and stars rotate at great speed around the gravitational center of the Milky Way – the Solar System is located on a local spiral arm called the Orion Arm, about 26,000 light-years (8 kpc)

from the galactic centre, and orbits the centre about once every 230 million years. At the centre of the galaxy, in the constellation Sagittarius, is a supermassive black hole (Sagittarius A*) with a mass of about 4 million solar masses [2]. The Milky Way is a member of a small cluster of galaxies called the Local Group; the Andromeda and Triangulum Galaxies are other large members of this group. There are also dwarf satellite galaxies (e.g. the Large and Small Magellanic Clouds, the Sagittarius Dwarf Galaxy, etc.) around the Milky Way. The image below schematically shows the Milky Way as viewed from above (the polar axis):

Figure 1: Top-down view (artistic representation) of the barred spiral structure of the Milky Way Galaxy. The galactic core (bulge) is seen in the centre, consisting of a dense crowd of stars. The arms are named in English: the galaxy has two main spiral arms (Scutum–Centaurus and Perseus arms) extending from the central bar. Also shown are secondary arms (such as Sagittarius–Carina) and the Orion Arm (Local Arm, the part where the Sun is located). The Sun's position is marked on the Orion Arm, approximately 26,000 light-years outside the galactic centre [4]. In light of the above general information, it is necessary to examine historical observations and modern multi-wavelength observation techniques and theoretical approaches in order to understand the Milky Way. In the following, first a historical overview of observational studies of the Milky Way at different wavelengths (radio, infrared, visible, ultraviolet, X-ray, gamma-ray) will be presented, then theoretical developments (galactic structure, dark matter, black hole at the galactic centre, formation and evolution models) will be discussed. In the last section, the obtained information will be summarised, and the remaining questions will be discussed.

Credict: NASA

2. Observational Aspects

When the Milky Way is examined in different regions of the electromagnetic spectrum, it exhibits different properties at each wavelength. As different telescope and detector technologies have developed, different components of our galaxy have been revealed. Important observations made at various wavelengths, from radio waves to gamma rays, are discussed below in a chronological perspective.

2.1 Radio Wavelength Observations

Until the 1930s, astronomical observations were made almost entirely at optical (visible light) wavelengths. Radio astronomy began in 1932 with an accidental discovery by American engineer Karl G. Jansky. While investigating sources of interference in radio communications at Bell Laboratories, Jansky noticed that a mysterious interference detected with his shortwave antenna was repeating itself with a four-minute delay every day. This matched the period of the Earth's rotation on its axis. Jansky determined that the signal came from a fixed celestial location and reported that the source was in the direction of the constellation Sagittarius, around the centre of the Milky Way [3]. In his famous article published in 1933, he explained “radio waves coming from outside the Solar System” and discovered the radio emission coming from the centre of the Milky Way [3]. This event is considered the birth of radio astronomy, and the unit of radio wave power is named “jansky” in his memory. After Jansky, Grote Reber built the first special radio telescope in 1937 and began to make systematic radio maps of the Milky Way. These pioneering studies showed that the galactic plane and central regions, hidden in visible light due to dust clouds, could be examined in radio waves. Major breakthroughs in radio astronomy took place in the 1950s. In particular, the discovery of the 21 cm spectral line of hydrogen gas revolutionised the mapping of the structure of the Milky Way. In 1944, an astronomer named Hendrik van de Hulst predicted theoretically that neutral hydrogen atoms would emit a very weak radio line at a wavelength of 21 cm due to the rotational (spin) transition. This prediction was confirmed experimentally by Harold Ewen and Edward Purcell of Harvard University on March 25, 1951 – neutral hydrogen gas in the Milky Way was detected for the first time at the 21 cm radio line [5]. This discovery made it possible to map the distribution of hydrogen gas across the galactic plane. Radio astronomers soon noticed that dense

regions of hydrogen formed a spiral pattern in the disk of the Milky Way. In the early 1950s, William Morgan and his colleagues optically studied the positions of young O- and B-type stars and H II regions, and from radio observations, they were the first to demonstrate that the Milky Way had spiral arms [4]. In 1951, Morgan mapped the structure of the nearest spiral arm of the Milky Way at the Yerkes Observatory in the United States, and these findings showed that our galaxy has at least two main spiral arms [4]. In the following years, as networks of radio telescopes grew, particularly in the 1960s and 1970s, detailed maps of the 21 cm hydrogen line were made. In this way, it was understood that the Milky Way has main arms called Perseus, Sagittarius (Sagittarius), Scutum-Centaurus (Shield-Centaurus) and Norma. It was determined that the Sun is located in a small arm between the main arms called the Local Arm (Orion Arm). Another critical discovery at radio wavelengths was indirect observations of a supermassive black hole at the centre of the galaxy. In the late 1960s, very long-baseline interferometry (VLBI) techniques detected a very compact and powerful radio source at the centre of the Milky Way. In 1974, Bruce Balick and Robert Brown published their discovery of this point radio source, called Sagittarius A* (Sgr A*) [6]. Sgr A* was located at the very centre of the Milky Way and was incredibly dense. Over time, more precise radio observations showed that gas and stars were orbiting Sgr A* at very high speeds. This data provided the first strong evidence for the existence of a black hole with a mass of about 4 million solar masses at the centre (later confirmed by observations at other wavelengths). Modern radio telescopes (such as VLBA, ALMA) continue to study both the large-scale structure of the Milky Way (such as radio “bubbles” or magnetic field structures emanating from the centre) and the area around the event horizon of the central black hole. In fact, in 2019, the Event Horizon Telescope collaboration first imaged the shadow of a black hole in another galaxy

(M87) with observations at 1.3 mm radio wavelength, and then in 2022, the shadow of the Sgr A* black hole. This is one of the most recent and striking contributions of radio astronomy to the understanding of the Milky Way.

2.2 Infrared Observations

Visible light observations made with optical telescopes are limited to the central and plane regions of our galaxy due to interstellar dust. Infrared astronomy allows us to see structures behind the dust because infrared radiation is less absorbed by dust clouds due to its long wavelength. The first infrared astronomy experiments were made with extra-atmospheric rockets and high-altitude aircraft starting in the 1960s. Discoveries in California in 1968 showed that the galactic centre had a strong infrared source. However, a real window was opened with the launch of the IRAS (Infrared Astronomical Satellite) satellite in 1983. IRAS is the world's first space-based infrared telescope and scanned 96% of the sky in 4 different IR bands, producing a comprehensive all-sky infrared map [5]. This map revealed the distribution of dense dust and molecular cloud structures in the plane of the Milky Way. In particular, a bright band of dust emission was seen extending across the entire galactic disk at far-infrared wavelengths around 100 microns. The IRAS data revealed that the bulge at the galactic centre was very bright in the infrared, containing dense star-forming regions and dusty clouds. Indeed, IRAS directly revealed the nucleus of the Milky Way, which is obscured from visible light for the first time [5]. IRAS also mapped the thermal dust radiation emitted by vast dark nebulae in the galaxy, detecting cold cloud complexes along the spiral arms. Following the success of IRAS, more advanced IR space telescopes came into play in the 1990s and 2000s. The COBE satellite, launched in 1989, measured the cosmic microwave background while also studying the Milky Way at infrared scales,

showing that the galactic centre has a bar-shaped structure. Missions such as the European Space Agency's ISO (Infrared Space Observatory) in 1995, NASA's Spitzer Space Telescope in 2003, and ESA's Herschel Space Observatory in 2009 observed star-forming regions, dust distribution, and the galactic centre of the Milky Way with increasing sensitivity. In particular, Spitzer obtained a detailed panorama of our galactic plane with large-scale infrared surveys such as GLIMPSE. Spitzer's images in the 3.6–8 micron band clarified the bar structure around the centre of the galaxy and traced the spiral arms. These data surprisingly revealed that the Milky Way has two main spiral arms, with the other arms being weaker and partial arms [7]. For example, analysis of Spitzer data in 2008 suggested that instead of the previously "four main arms" model, there are two dominant arms, Scutum–Centaurus and Perseus, and that the other two arms, Sagittarius and Norma, are secondary structures [7].

2.3 Visible Light (Optical) Observations

Optical observations of the Milky Way are one of the most established areas of astronomy. Since Galileo, countless telescope observations have examined the stellar components of our galaxy. Information has been obtained, especially in the visible light wavelength, about the galaxy's stellar population, open and globular star clusters, nebulae and some structures of the distant arms. In the 18th and 19th centuries, the star counting methods of William Herschel and his son John Herschel, although they gave an incorrect centre position due to the effect of dust, revealed the disk-shaped structure of the Milky Way for the first time. With the development of photographic techniques in the late 19th and early 20th centuries, panoramic photographs of the Milky Way were taken, and dark cloud structures in the sky were discovered. For example, in the early 1900s, E. E. Barnard catalogued the dark nebulae on the

Milky Way and showed the existence of dense dust regions in the galaxy. Significant advances were made in optical spectroscopy and photometry in the 1910s and 1920s. Vesto Slipher observed a redshift in the spectra of some "spiral nebulae" in the 1910s, providing the first clues that they were beyond the Milky Way [1]. While astronomers such as Kapteyn and Shapley debated the size and structure of the Milky Way in the 1920s, Edwin Hubble proved the existence of other galaxies by measuring the distance to Andromeda in 1924. This development made the Milky Way one of millions of galaxies in the universe. The first direct evidence of the spiral structure of the Milky Way at optical wavelengths came in the 1950s, when the distribution of young stars and nebulae was mapped, as mentioned above. In 1951, when W. W. Morgan examined the distribution of new OB stars in the sky, he discovered that these stars were arranged at successive distances in certain directions. This meant the existence of close spiral arm segments, and Morgan used this method to identify the Perseus Arm and the Sagittarius-Carina Arm [4].

3. Theoretical Aspects

3.1 Discovery and Modelling of Galactic Structure

and in the 18th century, various ideas were put forward about what the Milky Way was. Galileo's telescopic discovery (that the Milky Way was composed of stars) provided the first clue. Following this, Thomas Wright in 1750 and Immanuel Kant in 1755 conceptually proposed that the Milky Way was a giant disk-shaped star system [1]. Kant wrote that the Milky Way was a rotating disk and that some other nebulae in space could be similar "island universes". Although these ideas could not be directly tested at the time, they drew the first theoretical framework for the structure of our galaxy.

William Herschel performed the first modelling of the size and shape of the Milky Way using systematic star counts he made in the 1780s. By measuring the densities of stars in different directions, Herschel calculated that the galaxy was an approximately ellipsoidal disk with the Sun located near the centre. This model later became known as "Herschel's Grindstone Model". Although Herschel's placement of the Sun near the centre was an error (he did not know about the effects of dust absorption), he correctly captured the conclusion that the galaxy is planar. In the late 19th century, scientists such as Lord Kelvin and Simon Newcomb attempted to roughly calculate the mass of the Milky Way and the motions of the stars. However, the real theoretical breakthroughs came in the first quarter of the 20th century. Jacobus C. Kapteyn published his "Kapteyn Universe" model in 1922, based on photographic magnitude and parallax data. Kapteyn depicted our galaxy as a lens with a diameter of about 17 kpc (55,000 light-years) and containing the Sun near its centre [10]. This model also predicted that the galaxy would have a finite thickness in the vertical direction. Kapteyn assumed that the density of stars in the galaxy decreased from the centre outward, with the Sun slightly off-centre but nearly centred. However, this model did not account for the dimming effect of interstellar dust, thus significantly underestimating the true size of the galaxy. Kapteyn's student J. H. Oort and other contemporaries began investigating the rotation of the Milky Way in the 1920s. In 1927, Bertil Lindblad theoretically proposed the concept of a rotation curve, suggesting that galactic disks could rotate at different angular velocities. At the same time, Jan Oort defined two constants for galactic rotation (the Oort constants) based on the motions of nearby stars. In his work published in 1927, Oort showed that different regions of our galaxy rotate at different velocities, and therefore exhibit differential rotation. Oort also calculated the local mass density from the vertical velocity distribution of stars in the vicinity of the Sun, and

interestingly realised that there must be more mass than the visible stars provide (this would later become the problem of "dark matter"). In 1930, Robert Trumpler, by examining the distances and appearances of open clusters of stars, discovered that there was a dimming effect that increased with distance. Trumpler clearly demonstrated that starlight was absorbed by dust in the galaxy, and measured the rate of this absorption. This finding explained why Kapteyn's small galaxy model was wrong: the galaxy appeared smaller than it was because of the dust. After Trumpler's findings, Shapley's larger galaxy model was accepted, and it was understood that the Sun was ~8 kpc from the centre [1]. At this point, the approximate true size of the Milky Way (including a halo of stars extending up to 100 kpc in diameter) and its shape were generally established.

4. Discussion and Conclusions

We have developed a fairly comprehensive understanding of the Milky Way Galaxy based on the observational (Section 2) and theoretical (Section 3) information presented above. From an observational perspective, the application of multiwavelength astronomy has revealed all the different components of the Milky Way. Radio observations have mapped the spiral disk structure of our galaxy, determining the distribution of star-forming regions and the galactic rotation curve. Infrared observations have made visible the dusty and dense central regions hidden by optical light; the bar structure, dense star-forming regions and dark clouds at the galactic centre are only apparent in the IR band. Visible-light observations have enabled detailed studies of the stellar populations in our immediate vicinity and have revealed the relationship of our galaxy to neighbouring galaxies (e.g. satellite galaxies, stellar streams). Ultraviolet observations have helped us discover the hot and ionised components of the Milky Way – for example, the million-

degree halo of hot gas. X-ray observations revealed the high-energy arteries of our galaxy by revealing binary systems containing neutron stars and black holes, as well as supernova remnants. Gamma-ray observations shed light on both the galactic background created by cosmic ray interactions and giant-scale structures such as Fermi bubbles. When all these observational findings are evaluated together, it is understood that the Milky Way is a multi-component system: The thin and thick disks, the central core (bar and bulge), the halo of stars, the halo of hot gas and the halo of dark matter together form our galaxy. From a theoretical point of view, the Milky Way is an important example in both stellar dynamics and cosmology in modern astrophysics. The historical discovery of the structure of our galaxy is a beautiful example of the history of science: From Galileo's simple observation to the revolutionary results of Shapley and Hubble, our theoretical understanding has developed step by step. The problem of the rotation curve of the Milky Way provided one of the first and strongest pieces of evidence for the existence of dark matter, thus opening up a new field of physics research. Today, although dark matter is the dominant component of our galaxy's mass composition, its nature remains an unsolved puzzle – and the Milky Way is a natural laboratory for dark matter research. The black hole at the galactic centre has provided a critical testing ground for the intersection of general relativity and astrophysics. The confirmation of Einstein's predictions (e.g. gravitational redshift) by tracking stellar orbits has confirmed the validity of the theory in extreme conditions [11]. Furthermore, the Milky Way's situation (having a relatively calm core) allows us to compare it with examples of active galaxies regarding the role of supermassive black holes in galaxy evolution.

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Chapter 3

ASTROPHYSICAL (A,N) REACTIONS IN ODD-EVEN NUCLEI: ^{69}GA, ^{75}AS, AND ^{103}RH

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Introduction

Especially (α,n) nuclear reactions is crucial in nuclear astrophysics, as these reactions contribute to neutron production in stellar environments, influencing heavy element synthesis through the s-process and p-process. While numerous studies have focused on even-even nuclei, less attention has been given to odd-even nuclei, despite their distinct nuclear structure effects. This work focuses on three odd-even nuclei—^{69}Ga, ^{75}As, ^{103}Rh—to explore how unpaired nucleons influence reaction cross-sections and astrophysical S-factors.Cross-section calculations were performed using the TALYS 1.95(Goriely et al., 2008; Koning & Rochman, 2012) nuclear reaction code, which incorporates optical model potentials, compound nucleus formation, and pre-equilibrium mechanisms. Additionally, NON-SMOKER(T. Rauscher, 2000) was used to validate results, particularly for low-energy astrophysical conditions. Experimental data from EXFOR(EXFOR/CSISRS, n.d.) was used for model benchmarking.

The nuclei ^{69}Ga, ^{75}As, ^{103}Rh were analyzed for their astrophysical importance and their unique odd-even nuclear structure, the effect of nucleons on the reaction dynamics, especially the neutron emission probabilities.

Calculation Methods

The cross section is the probability that two particles will collide. For some nuclei, these measurements are difficult and sometimes impossible to obtain. Nuclear reaction codes can be used to eliminate such problems.

TALYS is an open-source nuclear reaction simulation code written in FORTRAN. It provides an integrated and flexible framework for modeling nuclear reactions, where users can adjust various model parameters to suit specific theoretical or experimental requirements. The code incorporates a

broad spectrum of nuclear reaction mechanisms, including direct reactions, pre-equilibrium reactions, compound nucleus formation, and fission processes.

TALYS allows researchers to simulate the interactions of a wide range of projectiles—protons, deuterons, alpha particles, tritons, neutrons, and photons—with target nuclei over an energy range from 1 keV to 1 GeV. The program includes multiple optical model potentials, level density models, and gamma-ray strength functions, enabling detailed cross-section and reaction rate predictions.

In this study, the Constant Temperature Fermi Gas Model (CTFGM) was employed for level density calculations. This model assumes a temperature-dependent distribution of nuclear energy levels and is particularly effective for describing level densities at moderate excitation energies (Goriely et al., 2008; Koning & Rochman, 2012)

NON-SMOKER is a theoretical nuclear reaction code based on the Hauser-Feshbach statistical model. It is designed to compute nuclear reaction cross sections for a wide range of target nuclei and energies, particularly for use in astrophysical applications such as r-, s-, and p-process nucleosynthesis.

The Hauser-Feshbach model assumes that the nuclear reaction proceeds through the formation of a compound nucleus, which reaches statistical equilibrium before decaying. The model includes critical quantum mechanical constraints such as angular momentum and parity conservation, and is especially effective when the level density of the compound nucleus is high.(NON-SMOKER)

EXFOR (EXchange FORmat) is a comprehensive nuclear reaction database that compiles experimental nuclear reaction data from published literature and laboratory reports worldwide. As of today, it contains

approximately 24,000 experimental datasets, including cross sections, angular distributions, and energy spectra for a wide variety of nuclear reactions. Maintained by the International Network of Nuclear Reaction Data Centres (NRDC) under the IAEA, EXFOR serves as a vital resource for validating theoretical models and supporting applications in nuclear physics and astrophysics.

The astrophysical S-factor, S(E), is defined to remove the strong energy dependence of the nuclear reaction cross section due to the Coulomb barrier and is expressed as:

$$S(E)=\sigma(E).E.exp(2\pi\eta) \quad (1)$$

where σ(E) is the reaction cross section at center-of-mass energy E, and η is the Sommerfeld parameter: $(Z_1.Z_2e^2)/\hbar\upsilon$, Here, Z_1 and Z_2 are the atomic numbers of the projectile and target nuclei, respectively, and υ is the relative velocity of the interacting particles. At low incident energies, nuclear cross sections are strongly suppressed by the Coulomb barrier, making direct experimental measurements of σ(E) extremely difficult or even impossible.In such cases, theoretically derived astrophysical S-factors provide a more reliable approach for estimating reaction rates (Yildiz & Aydin, 2016a, 2016b)

Results and Discussion

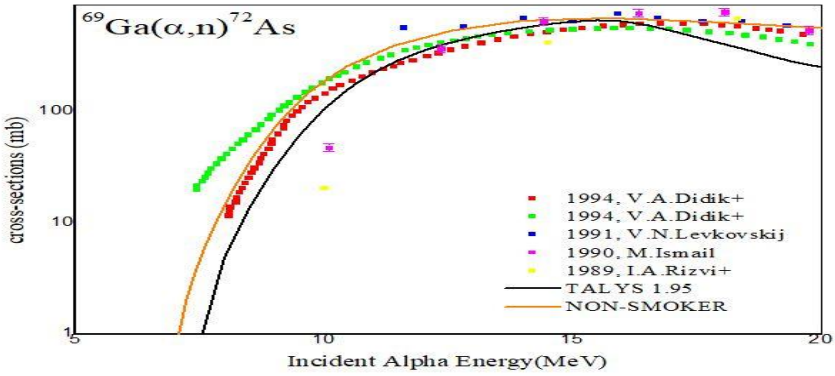

Figure 1. Cross-section values for $^{69}Ga(\alpha, n)^{72}As$ reaction

(Didik et al., 1994; Ismail, 1990; V. N. Levkovskii, 1991) It is seen that their studies are in great agreement with TALYS and NON SMOKER in the 8-16 MeV range.

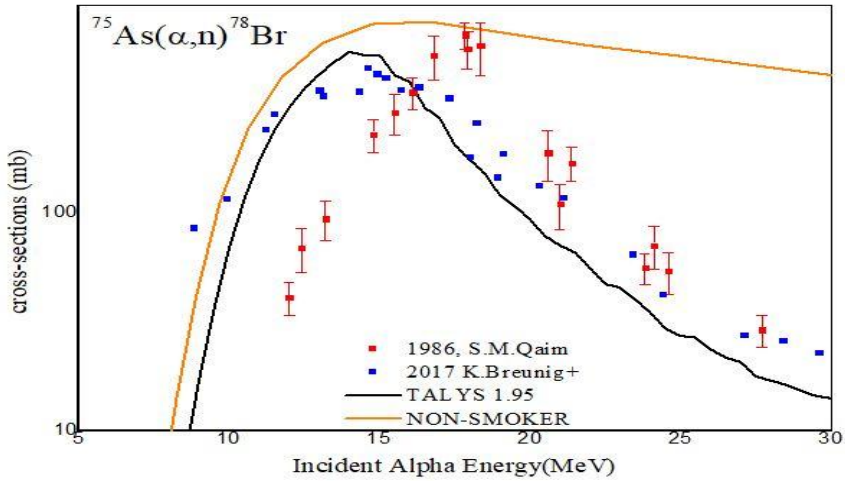

Figure 2. Cross-section values for ^{75}As (α, n) ^{78}Br reaction

TALYS and NON-SMOKER give parallel values in the 8-15 MeV range and start to separate from the peak point.(Qaim et al., 1986) data show similar properties but differ with the peak point. The values of (Breunig et al., 2017) are in good agreement with TALYS and NON-SMOKER, especially in the peak region.

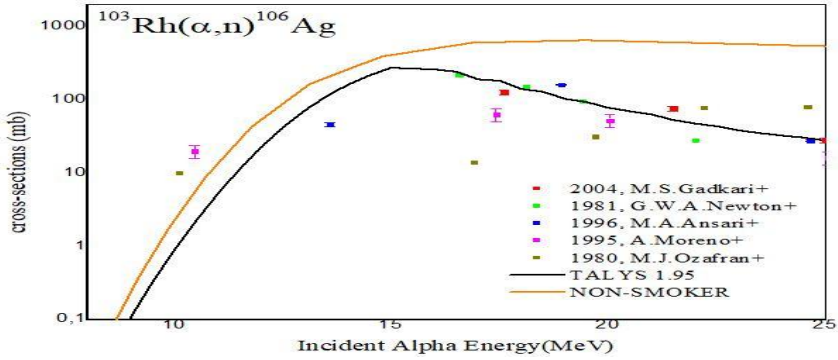

Figure 3. Cross-section values for ^{103}Rh (α, n) ^{106}Ag reaction

When the reaction cross sections are examined, TALYS and NON-SMOKER are in good agreement. However, we cannot say the same agreement for EXFOR ((A.Moreno et al., 1995; M. Afzal Ansari, 1996; M.S. Gadkari and N.L Singh, 2004; Newton et al., 1981) experimental data.

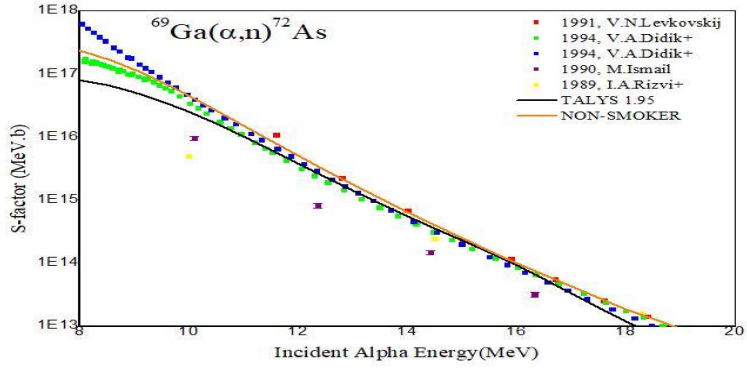

Figure 4. Calculated S-factor values for ^{69}Ga (α, n) ^{72}As reaction

When the Fig. 4 is examined, it is seen that EXFOR and TALYS, NON-SMOKER data are in great harmony.

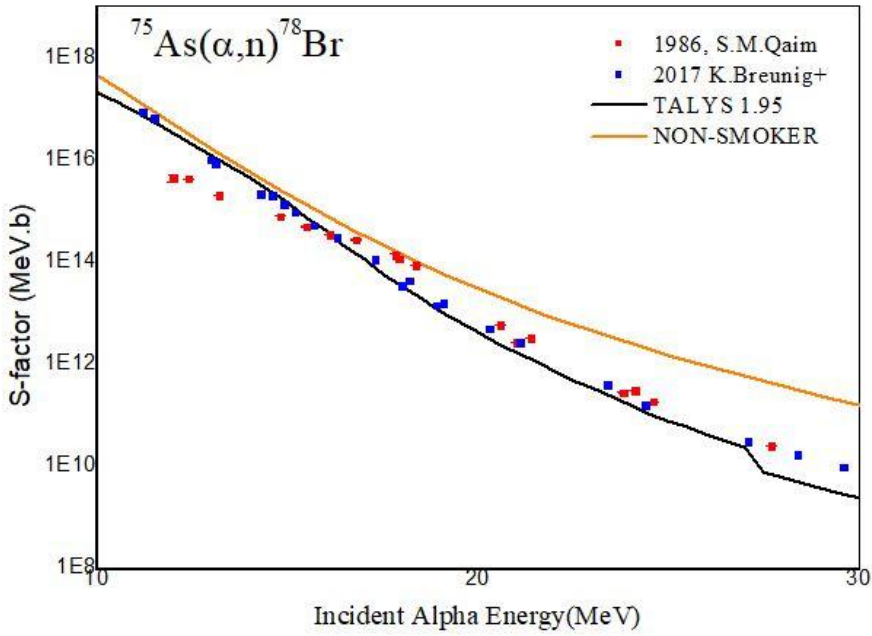

Figure 5. Calculated S-factor values for $^{75}As(\alpha, n)^{78}Br$ reaction

S factor values (Qaim et al., 1986) and (Breunig et al., 2017) are in great agreement and show similarities with TALYS and NON-SMOKER.

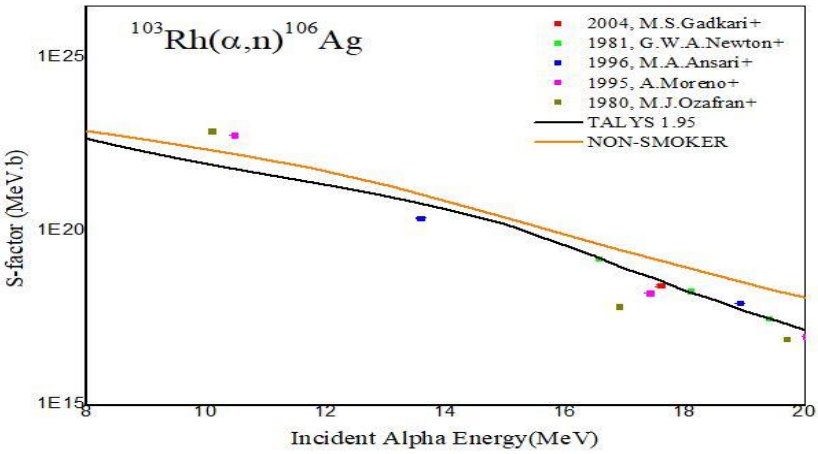

Figure 6. Calculated S-factor values for ^{103}Rh(α, n)^{106}Ag reaction

When the graph is examined, it is seen that EXFOR and TALYS, NON-SMOKER data are in great harmony.

Conclusion

The cross-sections and astrophysical S-factors of the (α,n) reactions on the odd-even nuclei ^{69}Ga, ^{75}As, and ^{103}Rh were systematically investigated. Theoretical calculations were performed using the TALYS 1.95 and NON-SMOKER codes, and the results were compared with experimental data obtained from the EXFOR database.

The results confirmed that odd-even nuclear structure, particularly the effect of unpaired nucleons, plays a significant role in shaping reaction dynamics and neutron emission probabilities. The derived astrophysical S-factors showed overall agreement with experimental trends, supporting the validity of semi-empirical approaches for estimating reaction rates when direct measurements are challenging.

These findings contribute to improving the predictive power of nucleosynthesis models by highlighting the necessity of including odd-

even nuclei in reaction network calculations. Future investigations should extend the dataset to additional nuclei and refine level density models to minimize theoretical uncertainties. In particular, expanding the analysis toward reactions relevant to the s- and p-processes will further enhance our understanding of heavy-element production in stellar environments.

The derived astrophysical S-factors demonstrated consistent trends with experimental values, validating the use of statistical models such as Hauser-Feshbach for odd-even nuclei. Moreover, the study highlighted the impact of nuclear structure—especially the presence of an unpaired nucleon on the reaction dynamics and neutron emission probabilities.

These findings emphasize the importance of including odd-even nuclei in nucleosynthesis network calculations and contribute to improving the reliability of astrophysical reaction rate predictions. Future work will focus on expanding the dataset to other odd-even and even-even nuclei and integrating refined level density models to reduce theoretical uncertainties.

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