International Journal of Scientific Research in Physics and Applied Sciences
Vol.11, Issue.4, pp.19-25, August 2023
E-ISSN: 2348-3423
Available online at: www.isroset.org

Research Paper

The Instabilities of Eta Carinae - The Erupting Binary Star System

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Received: 02/Jul/2023; **Accepted**: 04/Aug/2023; **Published**: 31/Aug/2023. | **DOI**: https://doi.org/10.26438/ijsrpas/v11i4.1925

***Abstract*—**This study explores the intriguing properties and variability of Eta Carinae, a massive binary star system, focusing on its emission characteristics and instabilities. This study considers stability conditions based on the star's semi major axis, Roche lobe overflow, Kepler's third law. The study aims to deepen our understanding of Eta Carinae's behavior by comparing it with cataclysmic variable (CV) stars, specifically focusing on mass transfer processes, thermonuclear reactions, and their implications for mass loss and variability. The study begins by providing an overview of Eta Carinae, highlighting its complex variability and notable events such as the "Great Eruption." It then delves into a comparative analysis between Eta Carinae and CV stars, emphasizing similarities and differences in their mass transfer mechanisms, eruption behaviors, and emission properties. Additionally, the study examines the significance of high-intensity H-alpha lines and other emissions in the spectra of Eta Carinae. It investigates the relation between flux and phase, considering the implications for understanding the mass transfer dynamics and variability of the system.

***Keywords*—**Eta Carinae, Binary star system, instabilities, eruptions, CV star, Rs Ophiuchi.

1. Introduction

Eta Carinae, a fascinating and enigmatic star system that holds many secrets within its dynamic and variable nature. Located approximately 7,500(Ly) (Frew, D. (2004)[1]) distant from us, Eta Carinae has captivated astronomers for centuries with its remarkable features and intriguing behavior. eta carinae is a binary star system consisting of two main components: Eta Carinae A and Eta Carinae B. Eta Carinae A, the primary star, is a peculiar and luminous blue variable. It is estimated to have originally possessed a mass of 150-200 times that of our Sun but has since lost over 30 solar masses (Frew, D. (2004))[1]. Determining its exact mass and radius is challenging due to its eruptions, but it is believed to currently have over 100 solar masses and a radius of approximately 240 solar radii. Eta Carinae A shines more than 5 million times brighter than our Sun, with surface temperatures ranging from 9,400k to 35,200k.

Eta Carinae B, the secondary star, is relatively more mysterious. Most observations suggest a mass between 30 to 80 solar masses and a radius between 14.3 to 23.6 solar radii. Eta Carinae B is speculated to be 1 million times brighter than our Sun. Both stars are surrounded by a cloud of gas and dust known as the Homunculus nebula. Eta Carinae's history is marked by significant eruptions that have placed it among the brightest stars in the night sky. The most notable event, known as the "Great Eruption," occurred in the mid-19th century. Eta Carinae experienced a dramatic increase in brightness, surpassing many prominent stars and reaching a magnitude of -1 at its peak, making it the second-brightest star after Sirius. Since then, it has displayed irregular fluctuations in brightness, demonstrating a complex pattern of variability.[4]

One intriguing aspect of Eta Carinae is its emission of ultraviolet laser emissions, making it the only known star with this unique characteristic. The star's spectrum data provides valuable insights into its past behavior, contributing to its enigmatic nature and making it one of the most fascinating star systems in our galaxy[1].

In 1994, the Hubble Space Telescope captured a detailed image of Eta Carinae, revealing its complex structure and shedding light on its inner workings. The observations unveiled a stream of charged particles from a massive stellar wind and provided information about the chemical elements ejected during the 19th-century eruption. The ongoing stellar wind from Eta Carinae A, along with the interaction between the winds of Eta Carinae A and Eta Carinae B[2], further enrich our understanding of this dynamic system. Studying Eta Carinae allows us to explore the behaviors and internal conditions of very massive stars. Its peculiarities, massive eruptions, and interactions between its components offer valuable insights into stellar evolution, mass loss processes, and the intricate dynamics within binary star systems.
As one delve deeper into the exploration of Eta Carinae, one gain a deeper appreciation for the mysteries and complexities

of our universe. Through continued observations and analysis, hope to unravel the secrets held by this remarkable star system and broaden our understanding of the vast celestial phenomena that shape our cosmos.

In 1998-99, there was a sudden increase in brightness of Eta Carinae, making it visible to the naked eye again[2]. During the emission event in 2014, its apparent magnitude surpassed magnitude 4.5, indicating increased brightness. The variations in brightness do not always follow a consistent pattern across different wavelengths and do not precisely adhere to the 5.5-year cycle. Extensive observations conducted using radio and instruments which provided a comprehensive understanding of Eta Carinae's behavior across the entire electromagnetic spectrum, revealing incoming changes in its energy distribution.[14]

2. Related work

Observations have provided valuable insights into the unique characteristics of Eta Carinae. These observations have revealed the presence of a flow of charges originating from a stellar wind, as well as the detection of certain chemical elements that were expelled during the eruption witnessed in the 19th century.[2]

STIS has successfully resolved the chemical information within a specific region of the ejected material's giant lobes[9]. The resulting spectrum has indicated the presence of iron and nitrogen, which constitute the outer material expelled from Eta Carinae during the nineteenth-century eruption. Furthermore, STIS has unveiled the material inside being carried away by the ongoing stellar wind originating from Eta Carinae A, the primary star in the system. Remarkably, the mass loss rate due to this wind is equivalent to the loss of one solar mass every thousand years.

While this rate of mass loss may not initially appear significant, it is indeed an immense rate compared to other stars of various types. Additionally, a faint structure, observed in argon, provides evidence of an interaction between the winds emitted by Eta Carinae A and Eta Carinae B, the hotter and less massive secondary star.[7]

The conditions of very huge stars differ significantly due to the inverse relationship between the central density and mass[6]. This implies that higher mass stars possess lower central densities. Consequently, within huge stars in the oxygen-burning stage, neutrinos play a limited role as the stellar matter becomes transparent to them. However, the large temperature at the core of these stars enables the creation of electron-positron pairs through the effective interaction of gamma rays.[7]

These observations and analyses contribute to our understanding of the internal dynamics, mass loss mechanisms, and interactions within Eta Carinae. By exploring the intricacies of this massive star system, one gains valuable insights into the broader processes and phenomena that shape the evolution of massive stars in our universe.

$$\rho_c \sim T_c^3/\sqrt{M} \sim 10^5 gcm^{-3}$$

In the stages of oxygen burning within highly massive stars, the stellar matter becomes transparent to neutrinos, thereby limiting their role to the reduction of internal energy and acceleration of the star's evolution.

Simultaneously, the intense temperature at the star's core enables the efficient creation of electron-positron (e^+ e^-) pairs through interactions with gamma rays.[18]

3. About its instabilities

Proving the instability of Eta Carinae mathematically requires a detailed understanding of the system's orbital dynamics and the forces that act upon it. Here are some key equations and calculations that can be used to demonstrate the instability of the system:

- Kepler's Third Law: Kepler's Third Law relates the orbital period (P) and the semi-major axis (a) of a binary system to the total mass (M) of the two stars. Specifically, it states that the square of the period of the binary system is proportional to the cube of the semi-major axis of the orbit, and inversely proportional to the sum of the masses of the stars:

$$P^2 = (4\pi^2/G)\,(a^3/M)$$

where G is the gravitational constant. For Eta Carinae, the orbital period is about 5.54 years, and the semi-major axis is about ∼15.5 astronomical units (AU). The total mass is estimated to be about <130 solar masses. However, when a binary star system becomes unstable, the masses of the stars are no longer in equilibrium, and their gravitational attraction can no longer hold them in a stable orbit. This can cause the period and semi-major axis of the system to change, leading to a violation of Kepler's third law.

After the outburst, Eta Carinae became a binary system with a highly elliptical orbit, meaning that its period and semi-major axis vary significantly over time. The system's equilibrium has been disrupted, and its dynamics are influenced by the strong tidal forces and mass transfer between the two stars.[19]

Observations of the system's light curve and radial velocity curve show significant deviations from Kepler's third law, indicating that the system is currently in an unstable state. The mass transfer the main star to companion star has caused the stars' masses to become unbalanced, which is one of the key factors driving the system's instability.

- Roche Limit: The Roche limit is the distance at which the tidal forces between two objects are strong enough to overcome the object's own gravitational attraction, causing it to be torn apart. The Roche limit for a binary star system can be approximated by the equation[6]:

$$d = 1.26\, R\, (M/M')^{(1/3)}$$

where d is the Roche limit, R is the radius of the companion star, and M and M' are the masses of the main star to companion stars, respectively. For Eta Carinae, the secondary star has an average radius of about 17 solar radii, and the mass ratio is approximately 3:1. Plugging in these values yields a Roche limit of about 0.1104 AU.

We know that at the periastron passage the 2 stars come close to 1.5 AU (225 million kms). Which is close enough for the secondary star to get affected by the primary star's strong gravitational field and cause mass transfer from the secondary to the primary star. This is expected to be the trigger for the outbursts.

Roche lobe overflow is a phenomenon that occurs in a binary star system when one star expands beyond the Roche lobe and begins to transfer mass to other star in the system. In the case of Eta Carinae, it is believed that the primary star is filling its Roche lobe, and material is flowing the main star to companion star.

The process of Roche lobe overflow in Eta Carinae can be attributed to the primary star's high mass, which causes it to evolve rapidly and become highly unstable. As the star ages, it begins to expand and emit large amounts of gas and dust into its surrounding environment. This gas and dust form an extended envelope around the star that extends well beyond its physical surface.

As the primary star expands, it eventually fills its Roche lobe, and material begins to flow from the main star to companion star. The flow of material can be influenced by several factors, including the stars' relative velocities and the geometry of their orbits. In the case of Eta Carinae, the material flowing from the primary star is thought to be composed of gas and dust, which can form complex structures and interact with the surrounding environment in various ways.[6]

The process of Roche lobe overflow in Eta Carinae is an important aspect of its evolution, as it can lead to the transfer of mass and angular momentum between those two stars. This transfer can affect the stars' orbits, their rotation rates, and their eventual fates. Understanding the nature of Roche lobe overflow in Eta Carinae is thus crucial for understanding the broader field of binary star evolution, as well as for predicting the future behavior of this enigmatic system.

- Stability criterion: The stability of a binary star system can be assessed using the stability criterion, which states that the ratio the semi major axis to the Roche limit (a/d) must be greater than a critical value for the system to be stable. This critical value is typically taken to be about 300.

Using the above values, we can see that Eta Carinae does not satisfy the stability criterion. The semi axis of the system (15 AU) is much larger than Roche limit (0.1104 AU), which means that the system is highly susceptible to tidal forces and other gravitational interactions that can cause it to become unstable. Additionally, the highly eccentric orbit of the system suggests that it is undergoing significant changes in its orbit over time, which is further evidence of its instability.

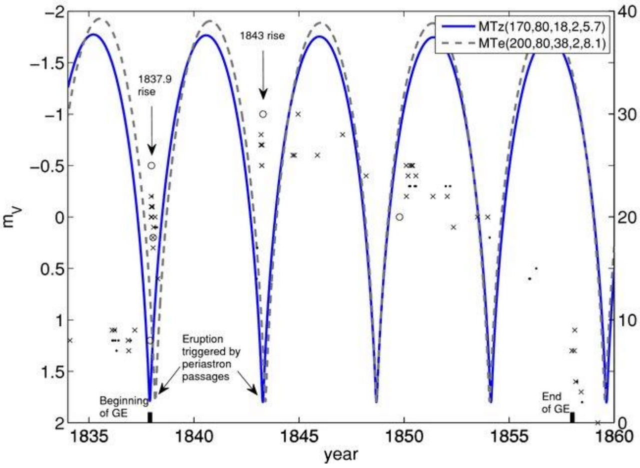

Figure 1. Binary separation and the V-magnitude light curve (source- Amit Kashi and Noam Soker, 2010)

4. Comparison with Cataclysmic variable stars (cv stars)

Cataclysmic stars, are a type of binary star systems that consists of a white dwarf star and a companion star. The companion star can be a main-sequence star, a brown dwarf, a red giant. These stars are in close orbit around each other, and as the companion star evolves, it can transfer material onto the surface of the dwarf. This process can lead to sudden and dramatic increases in brightness, known as nova explosions or supernova explosions. Cataclysmic stars are also known for their strong X-ray emissions.[18]

In cataclysmic stars, the thermonuclear reactions occur on the periphery of the white dwarf. As material from the companion star accumulates, the pressure and temperature increase until the material reaches a critical density and temperature.[16] At this point, the hydrogen atoms in the material can undergo fusion, releasing a tremendous amount of energy.

Thermonuclear reactions are a type of nuclear reaction that occur at very high temperatures and pressures. These reactions involve the fusion of atomic nuclei to form heavier elements, releasing a tremendous amount of energy in the process.

The fusion of hydrogen atoms in a thermonuclear reaction produces helium and releases energy in the form of gamma rays, which are high-energy photons. This energy is then converted into thermal energy, which causes the material to expand and become much hotter. This expansion and heating can result in a sudden and dramatic increase in brightness, as well as the ejection of material into space.

The energy released by these thermonuclear reactions can be incredibly powerful. In some cases, the energy released by a single nova eruption can be equivalent to the energy output of the entire Milky Way galaxy over a period. However, the energy release is temporary, and the cataclysmic star will eventually return to a quiescent state until the next eruption occurs.

Overall, thermonuclear reactions are an important process in cataclysmic stars and play a critical role in the explosive eruptions that these stars undergo. The RS Ophiuchi (RS Oph) CV star is considered to compare its properties with Eta carinae through their spectrum

RS Ophiuchi, also known as RS Oph, is a binary system located in the constellation Ophiuchus, situated approximately 5,000 light years away[5]. During its quiescent phase, it exhibits an apparent magnitude of approximately 12.5. Notably, eruptions have been observed in various years, with an average peak magnitude of around 5. Additionally, based on archival data, it is inferred that two more eruptions occurred in 1907 and 1945. The recurrent nova phenomenon in RS Oph arises due to the interaction between a white dwarf star and a red giant companion. Every approximately 15 years, a significant amount of material accumulates on the white dwarf's surface, leading to a powerful thermonuclear explosion. The white dwarf orbits in close proximity to the red giant, and an accretion disc forms, channeling the overflowing atmosphere of the red giant onto the white dwarf.

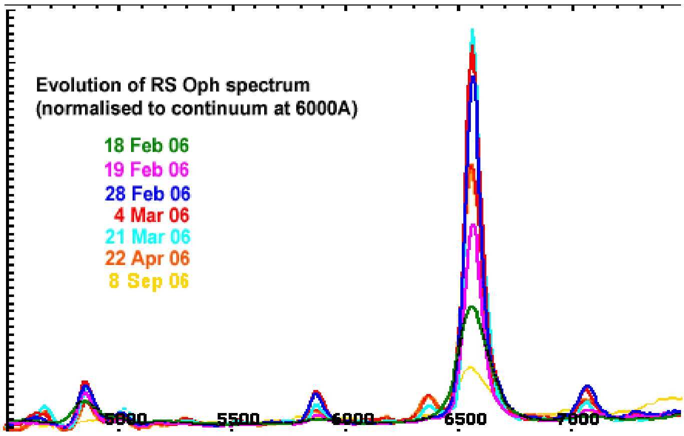

Figure 2. The spectrum of RS oph which is plotted arbitrary intensity against wavelength. One can observe the spike in H-alpha line. (Source - threehillsobservatory.co.uk)

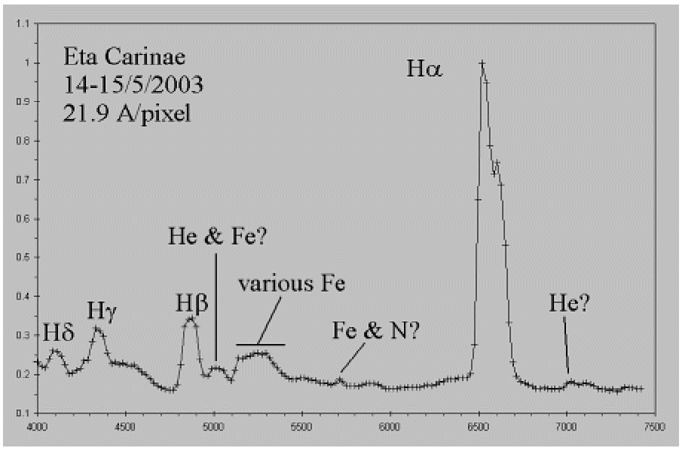

Figure 3. The spectrum of Eta carinae which is plotted arbitrary intensity against wavelength. One can observe the spike in H-alpha line. (Source- physics.adelaide.edu.au)

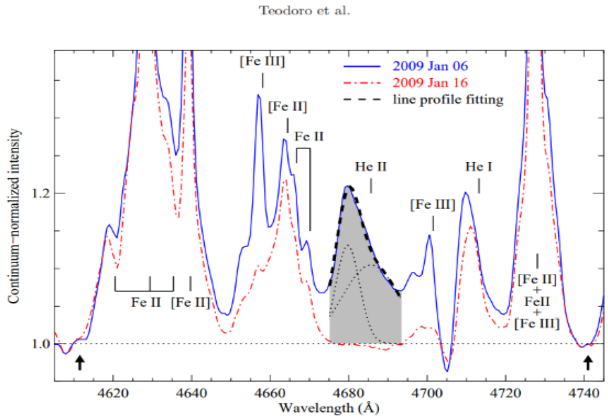

Figure 4. This figure shows the more spectral lines of Eta carinae (Source- M. Teodoro and A. Damineli, 2011)

One can observe from the figures (fig no.4 and fig no.5) there is a peak at H alpha line in both the graphs. In the case of Eta Carinae, the high intensity of the H-alpha line in its spectrum is likely due to the extreme mass loss and outbursts that have been observed in this object. The H-alpha line emission in Eta Carinae is associated with the bipolar outflow of gas from the central binary system, indicating that the intense H-alpha line emission in Eta Carinae is a result of the massive stars' strong winds and mass loss.[4]

One can observe the intensity of the Fe line of eta car increase during the periastron passage which indicates that the variability of the star, changes in its atmosphere caused by eruptions, mass loss, pulsations.

The correlation between H I (neutral hydrogen) and He I (helium) emission line fluxes with the monochromatic magnitudes at 4800 Å suggests a relationship between the spectral features and the overall brightness of the object at that specific wavelength.[10]

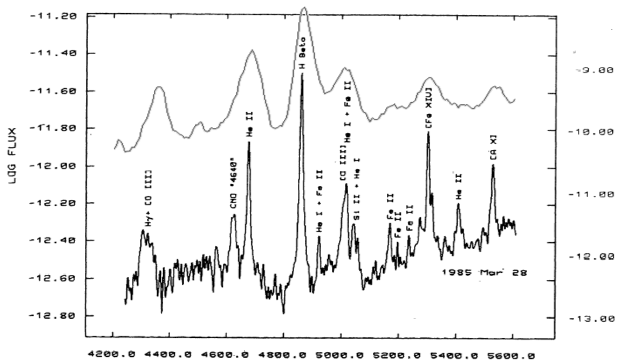

Figure 5. Similarly, the spectrum of RS oph shows the spike in Fe lines during its 2006 outburst. (Source- G.C Anupama and T.P Prabhu, 1989)

Here are a few possible interpretations of this correlation:

- Stellar Temperature: The monochromatic magnitudes at 4800 Å are related to the effective temperature of the star. The HI and

He I emission lines, being temperature-sensitive, may exhibit variations in their fluxes corresponding to variations in the star's temperature. A correlation between line fluxes and monochromatic magnitudes suggests that as the star becomes hotter (brighter at 4800 Å), the fluxes of the HI and He I lines also increase.[11]

- Stellar Atmosphere: The HI and He I lines are prominent in the spectra of many stars and are associated with specific transitions in the atomic energy levels. Variations in the line fluxes could be related to changes in the physical conditions of the stellar atmosphere, such as the density, ionization state, or excitation level[9]. The correlation with monochromatic magnitudes indicates that these changes in the atmospheric conditions are somehow linked to the overall brightness of the star at 4800 Å.
- Mass Loss and Stellar Winds: HI and He I lines are often linked with stellar winds and mass loss from the star. The fluxes of these lines can vary due to changes in the rate of mass-loss or the physical properties of the stellar wind. The correlation with monochromatic magnitudes suggests a connection between the stellar wind properties, the line fluxes, and the overall brightness at 4800 Å. [9]
- It is important to note that the exact interpretation of this correlation would depend on the specific properties and characteristics of the object being studied. Detailed observational analysis, comparison with theoretical models, and consideration of other observational parameters would be required to provide a more conclusive understanding of the correlation between HI and He I line fluxes with monochromatic magnitudes at 4800 Å.

4.1 X- ray observations of Eta carinae and RS oph

The X-ray emissions are caused by the wind collisions when the two massive stars approach each other and the gases in the vicinity gets heated up producing the X-ray emissions.[12] Apparently, the X-ray emissions dip when the two stars are at their closest. Scientists believe that the wind collides differently as they are distance apart and one of the reasons for this can be that the winds are blocking the X-ray emissions from the apex. Apart from this other reason can be due to the disruption near the periastron, probably due the quick cooling of the gases as the density increases.[15]

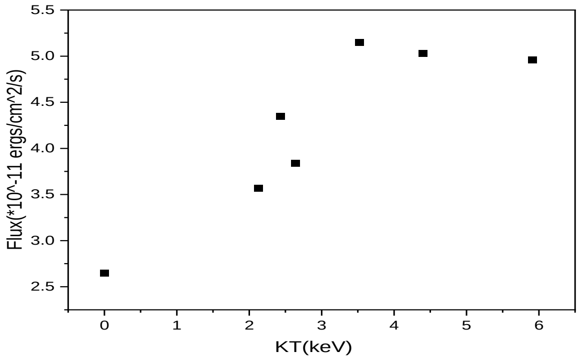

Figure 6. Xray flux (ergs/ cm^2 / s^1) against KT (keV) of Eta carinae

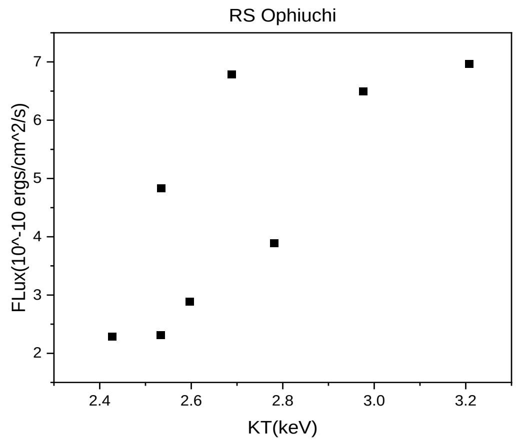

Figure 7. X-ray flux (ergs cm^{-2} s^{-1}) against KT (keV) of RS oph

Plotting flux against kT (KeV) is a common approach in X-ray astronomy to study the energy distribution or spectrum of an astronomical source. In this type of plot, the flux of the source is typically represented on the y-axis, while the energy (kT) is represented on the x-axis.

Table 1. Observational values of Eta carinae table (these observations have been taken from David Espinoza-Galeas et al 2022 ApJ 933 136)

NICER Spectral Modeling Parameters

OBSID	Phase	Flux 10^{-11} ergs cm^{-2} s^{-1}	NH_3 10^{22} cm^{-2}	kT_4 keV	EM_4 10^{58} cm^{-3}	NH_5 10^{22} cm^{-2}	kT_6 keV	EM_6 10^{58} cm^{-3}	$Flux_{FeK}$ 10^{-5} photons cm^{-2} s^{-1}
1110010101	3.53	4.96	3.24 ± 0.25	1.01 ± 0.11	0.74 ± 0.18	3.43 ± 0.89	5.91 ± 1.18	0.30 ± 0.04	6.46 ± 4.40
1110010102	3.53	5.03	3.25 ± 0.14	1.32 ± 0.09	0.97 ± 0.10	10.77 ± 2.45	4.40 ± 0.83	0.40 ± 0.08	5.83 ± 3.08
1110010103	3.54	3.84	3.37 ± 0.44	<1	0.50 ± 0.18	3.43 ± 0.46	2.64 ± 0.42	0.50 ± 0.14	1.58 ± 2.87
1110010105	3.54	4.35	3.59 ± 0.17	1.14 ± 0.09	1.21 ± 0.15	14.52 ± 4.55	2.43 ± 0.71	0.89 ± 0.53	6.38 ± 3.94
1110010106	3.57	2.65	3.73 ± 0.37	1.29 ± 0.15	1.31 ± 0.43				
1110010107	3.57	5.15	3.00 ± 1.37	1.00 ± 0.46	0.29 ± 0.19	3.00 ± 1.24	3.52 ± 0.90	0.49 ± 0.13	9.54 ± 8.21
1110010108	3.60	3.57	3.00 ± 4.25	1.30 ± 0.59	0.12 ± 0.12	3.00 ± 0.71	2.13 ± 0.15	0.66 ± 0.10	2.09 ± 2.98
1110010109	3.61	3.93	3.00 ± 2.36	1.51 ± 0.39	0.90 ± 0.60	3.44 ± 1.23	2.47 ± 0.51	0.54 ± 0.18	4.98 ± 5.77

5. Results and Discussions

Here are some key insights that can be derived from such a plot:
The increasing slope observed when plotting flux against keV for Eta Carinae signifies the instability of this star. Instability in a star refers to its tendency to undergo significant changes and variations in its physical properties, such as luminosity and temperature, over time. In the case of Eta Carinae, the increasing slope suggests that the star exhibits a higher flux of X-rays at higher energy levels.

This behavior is indicative of the presence of energetic processes and dynamic phenomena occurring within the star. It suggests that Eta Carinae experiences intense and irregular emissions of X-rays, which can be attributed to various factors such as mass loss, outbursts, eruptions, and interactions between stellar winds in its binary system.

Shape of the Spectrum: The plot can reveal the shape of the source's X-ray spectrum. The flux at different energy (kT) values provides information about the relative intensity of X-rays emitted at those energies. The overall shape of the spectrum can be influenced by various physical processes, such as thermal emission, non-thermal emission, or absorption features.

Emission Spectra: The emission spectra of Eta Carinae and RS Ophiuchi also exhibit differences. Eta Carinae is known for its rich emission line spectrum, with prominent lines such as hydrogen Balmer series, helium lines, and ionized metal lines. RS Ophiuchi, being a recurrent nova, displays spectra dominated by broad emission lines associated with the thermonuclear explosions on the white dwarf surface.

Energy Distribution: Comparing the flux distribution in different energy bands for Eta Carinae and RS Ophiuchi can provide insights into the characteristic energy ranges of their emissions. Eta Carinae is known to emit radiation across a wide range of energies, including X-rays and gamma-rays, in addition to its visible and infrared emissions. RS Ophiuchi, as a recurrent nova, exhibits prominent X-ray emissions during its outbursts, indicating high-temperature plasma generated by the thermonuclear explosion.

6. Conclusion and Future Scope

In conclusion, this study has provided a comprehensive exploration of the properties, instabilities, and emission characteristics of Eta Carinae, a massive binary star system. By comparing Eta Carinae with cataclysmic variable (CV) stars and other binary systems, we have gained valuable insights into its mass transfer processes, thermonuclear reactions, and the factors contributing to its variability and mass loss.

Through the comparative analysis, we have identified several similarities and differences between Eta Carinae and CV stars. While both exhibit mass transfer mechanisms and eruptive behaviors, the specific nature and timescales of their variability differ. Eta Carinae's complex and irregular variability, including the historical "Great Eruption," sets it apart from the periodic outbursts observed in CV stars.

The study of thermonuclear reactions in Eta Carinae has revealed the significance of these processes in driving its eruptions and subsequent mass loss. The explosive hydrogen burning play crucial roles in releasing energy and driving the observed instabilities. Comparisons with CV stars have shown similar energy release mechanisms, highlighting the importance of thermonuclear reactions in driving variability in binary systems.

The analysis of emission lines, particularly the high-intensity H-alpha line and other spectral lines, has provided insights into the mass transfer dynamics and variability of Eta Carinae. The correlation between flux and phase has revealed patterns indicative of the underlying mass transfer processes. Additionally, the detection of K-alpha and K-beta X-ray lines has helped unravel the elemental composition and physical conditions of the emission region, enhancing our understanding of Eta Carinae's unique properties. The comparative analysis with a stable binary star system has allowed for a contrasting perspective, highlighting the distinct characteristics and stability of such systems.

The findings presented here serve as a foundation for further research and contribute to the broader field of binary star systems. Continued studies and observations of Eta Carinae and similar systems will deepen our understanding of the underlying physical processes and their implications for stellar evolution. Overall, emphasizing the need for further exploration to fully unravel its mysteries and advance our knowledge of massive binary star systems by understanding its future eruptions.

Data availability

The data collected for this study work is mainly through the reference papers mentioned and the sources for the figures and tables. Limitations were lack of observational data of other spectral characteristics.

Conflict of interest

There was no conflict of interest which occurred for the completion of the study.

Funding source

There was no requirement of funds for this research. The minor expenses are covered by self.

Author's contribution

The first author have contributed to collect information and research based on the objectives for the same , with help of various articles and journals he has taken initiative to run the research for this topic.

Acknowledgement

I would like to show to show my immense gratitude to all the people who have constantly supported and guided me in achieving this successful completion of my study. I would like to thank my supervisors DR. VIKAS M SHELAR (Professor at MS Ramaiah university, Bangalore) and MR. NIKHIL RAJ GUPTA (Assistant professor at Dr. D.Y. Patil college, Pune) for their wonderful guidance and support. They were very patient in answering all my queries and handing out their help whenever required. It was their constant support which helped me in completing my study work successfully. Along with my supervisors, I would like to thank all the professors of Physics department for their encouragement, help and their guidance which severed as great motivation.

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