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Report Form

Discovering New Wolf-Rayet Central Stars of Planetary Nebula

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Acknowledgement

I want to express my heartfelt gratitude to my supervisor, Professor Parker, for the opportunity to be involved in his outstanding projects and for his invaluable advice and encouragement. I am also deeply thankful to Dr. Ritter for his patience and unwavering guidance throughout my journey. Additionally, I appreciate everyone at LSR; their kindness and excellence have been a great source of inspiration for me. Last but not least, I sincerely thank the Laidlaw Foundation and HKU horizons office for providing me with such a valuable opportunity.

Abstract

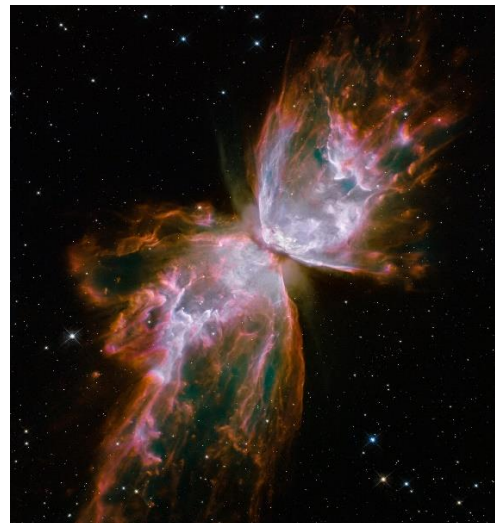
Studying planetary nebulae (PNe) is crucial for understanding late-stage stellar evolution and the chemical evolution of our entire Galaxy. This research focuses on discovering the central star of a planetary nebula (PN) that mimics massive Wolf-Rayet (WR) stars. My tasks include sorting data tables, processing fits files, and measuring the intensity of different emission lines. The primary method used in the project is analysing the data from the cutting-edge database ---- HASH (Hong Kong / AAO/ Strasbourg H-alpha PN research platform). Using the data available in HASH, we investigated the features of these candidates and analysed their properties to facilitate quantitative classification. It dramatically increases the number of central stars of planetary nebula that mimics Wolf-Rayet features, which can significantly facilitate further understanding of late-stage stellar evolution.

Introduction

A planetary nebula is a fascinating astronomical phenomenon that occurs at the end of the life of a star of intermediate mass, about 1-8 solar masses. The formation of a planetary nebula begins when a star exhausts its nuclear fuel, causing it to expand into a red giant. In this phase, the star's outer layers become increasingly unstable and are eventually expelled into space due to strong stellar winds. Once the red giant's atmosphere has dissipated, it creates a shell of ionised gas surrounding the remaining core. This core emits intense ultraviolet radiation that ionises the expelled gas. The ultraviolet light being absorbed energises the surrounding shell of nebulous gas, making it glow with vibrant colours and creating a striking planetary nebula. Over time, the planetary nebula will disperse into the interstellar medium, enriching it with heavier elements produced during the star's life and death. This process contributes to the cosmic cycle of matter, helping to form new stars and planets.



NGC 7293, the Helix Nebula

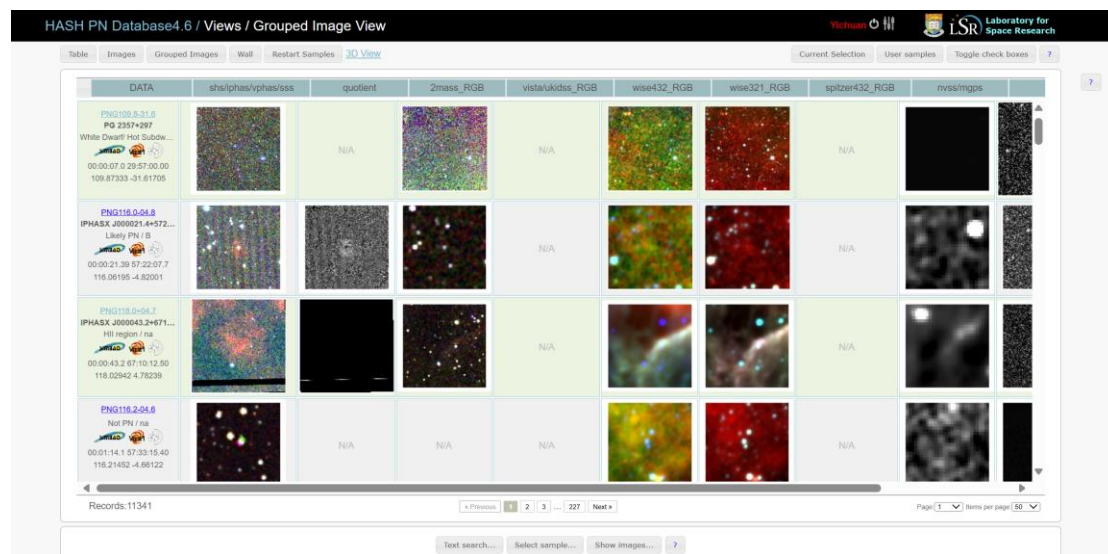


NGC 6302 Butterfly Nebula

It's vital to study PNe astrophysics since it profoundly facilitates our understanding of both the late-stage stellar evolution of low and intermediate-mass stars and the chemical evolution of our entire Galaxy (Frew & Parker 2010; Frew & Parker 2012). Even though they are ephemeral, compared with considerably longer stellar evolution, they are very luminous, making them

visible to great distance. The ionised shells of PNe showcase numerous strong emission lines, making them excellent subjects for plasma physics studies. By analysing these strong lines, many properties, such as the expansion velocity, size, and chemical components of PNe, can be revealed, which further probes the physics and timescales of stellar mass loss. Additionally, PNe enables us to derive the luminosity, temperature, and mass of their central stars (CSPNe) and the ejected gas's chemical composition. Their intricate shapes offer insights into their formation and evolution, the processes of mass loss, and the potential influence of magnetic fields, binary central stars, or even massive planets. In summary, PNe is a powerful astrophysical tool, providing a unique window into the soul of late-stage stellar evolution (Karakas et al. 2009).

Professor Parker has led programs that have doubled the totals accumulated over the previous 250 years (Parker, Phillipps & Morgan 1999). Following this motivation, they have provided an accessible, reliable, online "one-stop" SQL database for essential, up-to-date information for all known Galactic PN called HASH (Hong Kong / AAO/ Strasbourg H-alpha PN research platform). The specific project below will be built on and make use of this world-leading new resource.



Screenshot of HASH database

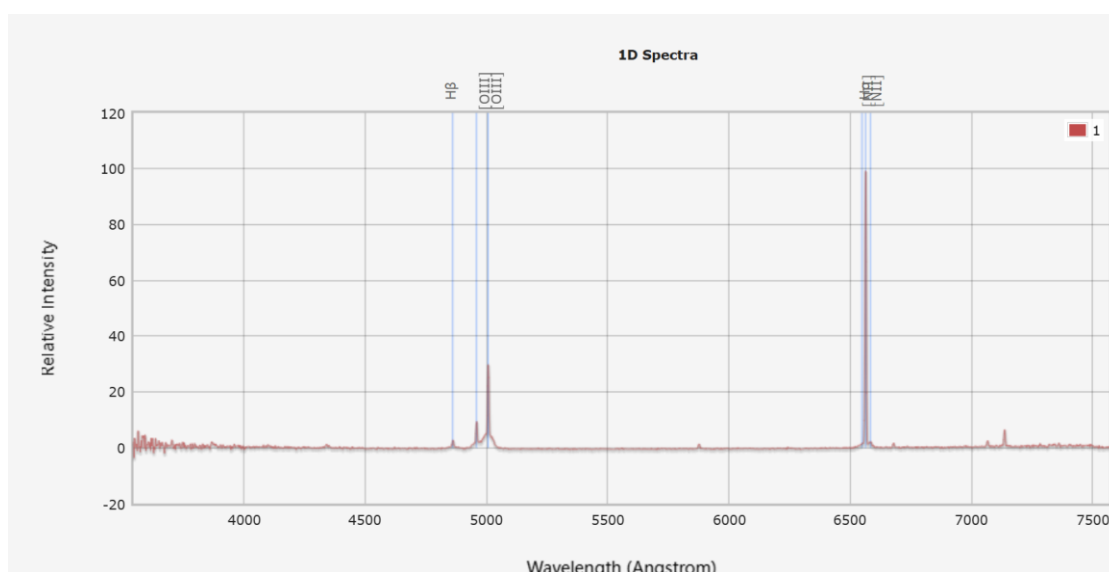
In this study, we focus on the discovery of planetary nebulae (CSPNe) that show Wolf-Rayet (WR) emission features. A Wolf-Rayet star is a rare and massive type of star that is in a late evolutionary stage. These stars are known for their strong stellar winds, which can blow away significant amounts of their mass. They exhibit broad emission lines in their spectra, indicating the presence of elements like helium, carbon, and nitrogen. Wolf-Rayet stars typically have surface temperatures exceeding 30,000 Kelvin and are often more than 25 times the mass of the Sun. Their intense luminosity and rapid evolution make them important contributors to the chemical enrichment of the universe, often leading to supernova explosions at the end of their life cycles.

This research centres on identifying the central star of a planetary nebula (PN) that exhibits characteristics of Wolf-Rayet (WR) stars. This study aims to enhance our comprehension of the processes involved in late-stage stellar evolution by analysing data from the HASH database.

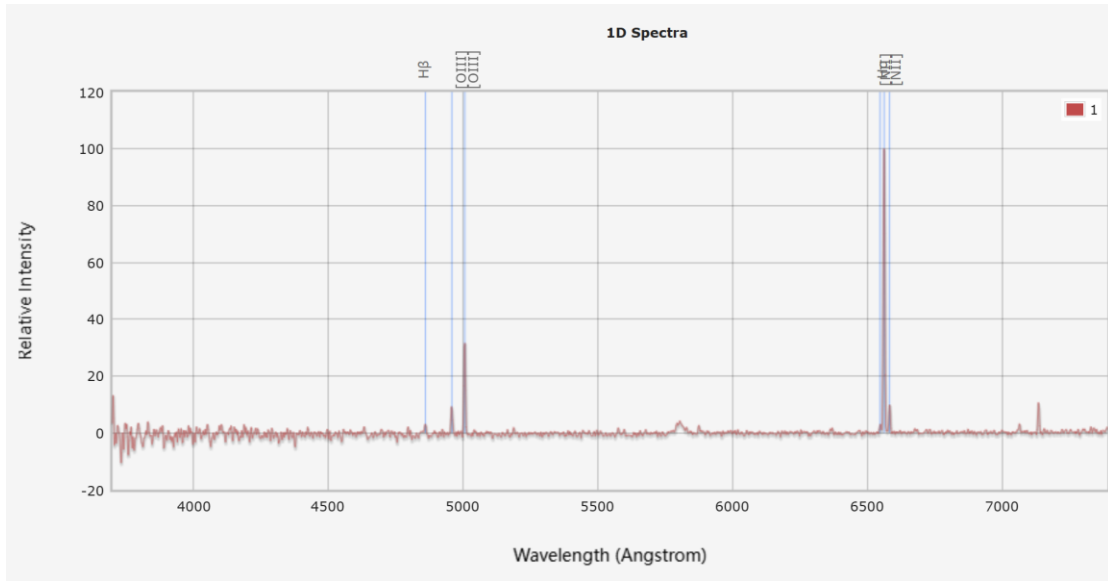
Methodology

I want to kindly note that the truly professional classification and data processing in astrophysics is beyond my current academic level, and my main job was assisting Professor Parker and Dr Ritter while trying my best to learn relevant skills. Tasks I undertake include sorting data tables, processing fits files, and measuring the intensity of different emission lines. Also, all the data still requires further processing and updating.

Professor Parker has long been making detailed notes on each PNe recorded in HASH. Based on these comments, Dr. Ritter developed a program to find all CSPNe with WR features mentioned in the note. While reading several academic essays to absorb new knowledge, I collected the properties of CSPNe from the SIMBAD database and sorted them into table. In this process, I became familiar with the HASH and SIMBAD databases and learned how to apply Python programs to capture and classify all the data. A few examples of [WR] CSPN spectra are shown below.



Spectra of PNG 313.4+06.2



Spectra of PNG 040.1+03.2

However, given that the coordinates of objects may vary slightly between different databases, a single input could lead to 0/1/2 outputs in SIMBAD. Thus, it takes me a long time to examine all the data individually to ensure a one-to-one correspondence relationship. After sorting out all the data, I picked out all the CSPNe with the WR feature but without any classification records, where we have our first group of candidates for newly discovered WR stars. The table is attached as below.

idPNMain	PNG	RA	DEC	dist	main otype	otype	spectral type	classificatio notes
3069	349.7+04.0	02:46.1	-35:09:02.0	0.03	PlanetaryNeb_Candidate	PN,PN?	none	Compact/stellar image with evidence of close-in surrounding very faint nebula
9967	040.1+03.2	53:09.4	52:41.0	0.02	PlanetaryNeb ~	PN,ISM	none	Probable [WR] CIV broad feature at 5800 A
2804	309.8-01.6	54:22.3	-63:37:18.0	0.73	PlanetaryNeb ~	PN,NIR,*,IR,	none	Compact PN confirmed spectroscopically M5SSO Feb 2007; [WR] features in
2820	313.4+06.2	05:32.2	-55:07:44.0	0.03	PlanetaryNeb ~	PN,PN?	none	Compact PN confirmed spectroscopically M5SSO Feb 2007; H-alpha in red [C
4110	007.9+10.1	26:38.1	-16:48:29.63	0.4	PlanetaryNeb ~	PN,NIR,*	none	Unresolved in PANSTARRS; Possible [WR] CSPN with possible [NII]/[CIII]/[CIV] fe
276	017.0+11.1	42:14.4	-8:43:18.4	1.3	PlanetaryNeb ~	PN,MIR,Em	none	Compact oval PN but has multipolar features in PANSTARRS so likely actually
226	010.4+04.5	52:04.8	-17:36:06.2	1.49	PlanetaryNeb ~	PN,*,G,IR	none	Compact oval ring in PANSTARRS with CSPN. High excitation. Acker spectrum
10960	079.8-10.2	15:06.6	+33:58:18.4	0.44	PlanetaryNeb ~	blu,PN,*,HS	none	Faint Oval PN; GTC OSIRIS spectrum on 21/08/2016 confirms; has blue centra
22850	056.1-03.8	49:53.7	40:15.0	0.12	PlanetaryNeb_Candidate	PN?	none	French amateur discovery PN Confirmed spectroscopically by French Amate
4856	267.3-03.9	43:29.4	-48:54:47.30	0.52	PlanetaryNeb ~	PN,cm,G,IR,	none	Compact high excitation PN; Suarez ESO 1.5m spectrum has [NII]-H-alpha; [C
3184	355.9-04.4	53:40.3	-34:43:41.0	0.03	PlanetaryNeb ~	PN,IR,Rad	none	Bipolar/boxy high excitation PN; also observed 6DF 210803; also now known i
2977	336.5+05.5	11:12.9	-43:56:22.0	0.1	PlanetaryNeb ~	PN,NIR,*,PN	none	Round nebula with blueish prominent [WR] CSPN; SAAO 1.9m June 2024 spe
2657	284.2-05.3	01:18.8	-61:52:03.9	0.17	HotSubdwarf_Candidate	blu,*,HS?	none	[WCS-6] (K); Faint; circular high excitation PN- has annulus + circular halo. CSPN is of [W
2923	328.8-01.1	03:41.4	-54:02:04.0	0.03	RefNeb ~	HII,PN,RNe,	none	; Nebula close to bright star; PM15; [WR] features; also observed SA180501; f
3289	359.8+03.5	31:47.8	-27:09:19	0.03	PlanetaryNeb_Candidate	PN,IR,PN?	none	; Faint; small; slightly oval PN; also observed SA300603 6D040802; H-alpha>
3191	356.0-04.2	53:04.9	-34:28:39.0	0.03	PlanetaryNeb ~	PN	none	; Faint; oval; high excitation PN with enhanced opposing sides - bipolar core?
947	307.5-04.9	39:35.1	-67:22:51.9	0.25	PlanetaryNeb ~	PN,NIR,cm,	none	Of(H)** ; Famous bipolar PN; has Binary CSPN period ~1.8 days; Acker spectrum has
1207	355.9-04.2	52:58.9	-34:38:23.0	0.77	PlanetaryNeb ~	PN,MIR,*,G,	none	wels; wels** ; Compact; bright PN; lobes give an apparent S-shaped bipolar with faint CSP
289	019.4-05.3	45:55.1	-14:27:37.9	0.31	PlanetaryNeb ~	PN,NIR,cm,	none	wels; wels** ; [WCI]**

First version of candidates

After all the candidates were picked out, we started measuring the intensity of

different emission lines to ensure the quantitative classification. Under the guidance of Dr. Ritter, I have a better command of Python, focusing on the usage of Pandas and Numpy, to further prepare myself for the data analysing task.

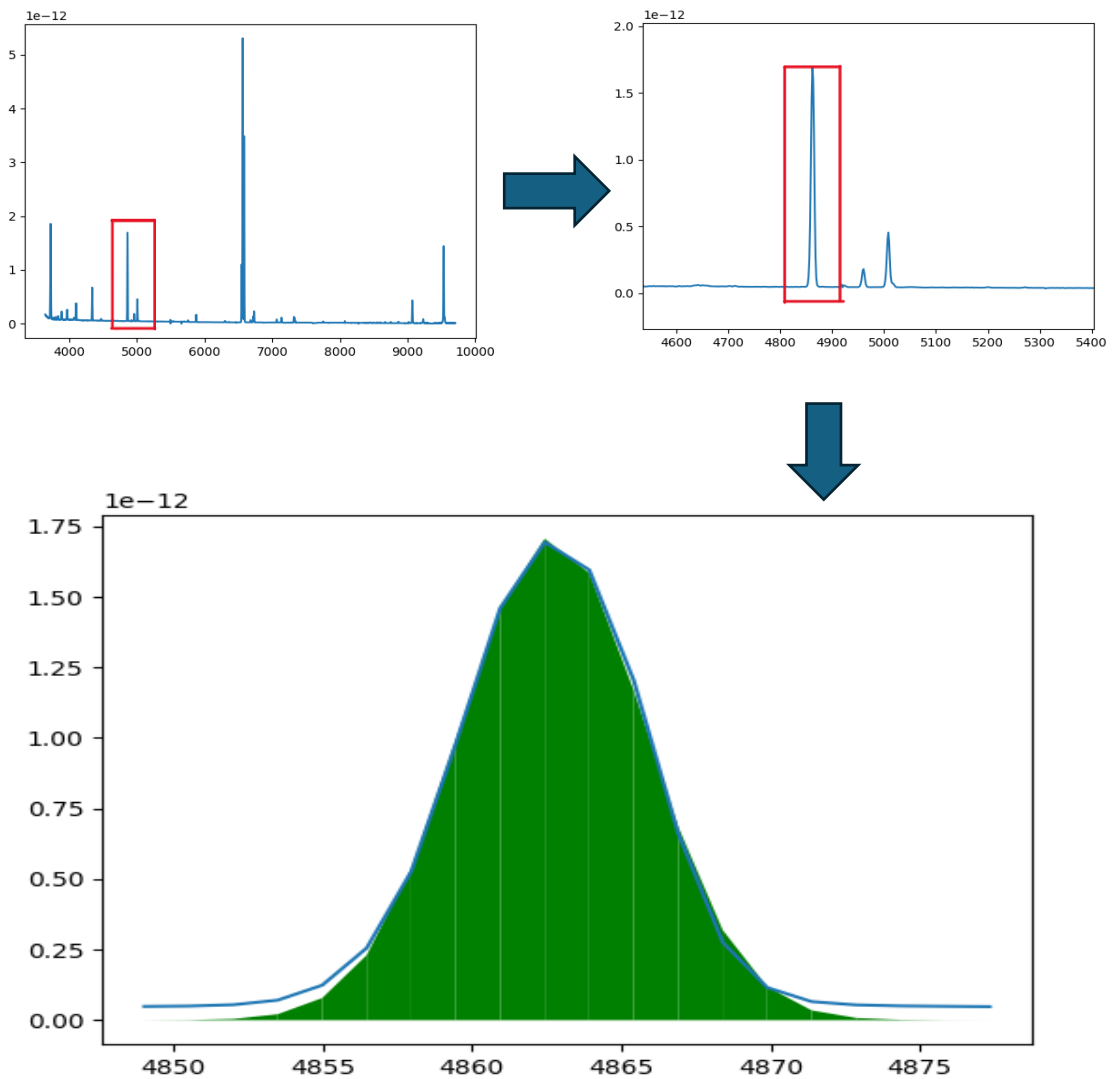
The initial step in processing fits files involves the removal of the continuum, which refers to the smooth and continuous spectrum of electromagnetic radiation emitted by astronomical objects, as opposed to discrete lines at specific wavelengths. To quantify absorption features in spectra, it is essential to eliminate the overall concave shape of the spectrum. This normalization process, also known as "continuum removal", enables the comparison of spectra collected from different instruments or under varying lighting conditions. Under the instructions of Dr. Ritter, I have learned to automate the continuum removal process using Python programming techniques.

After removing all the continuum of the spectrum, we measured emissions lines that are essential to the classification of all the spectrum, including [SII] 6716 & 6731, [NII] 6548 & 6583, H α 6563, H β 4861, [OIII] 4959, 5007. The line intensities were measured by integration over the line (area in emission over the continuum). I learned various methods from Dr. Ritter to measure emissions lines' intensity, from interactive images to automatic processing.

Now, I will introduce the method of measuring emissions lines. We set a function named `fit_lines` with three inputs: `fitsFile`, `RoughxRange`, and `save`, referring to the `fitsFile` of PNe, the rough range for each emission line (ie. (4820,4900) for H β 4861, (4945,4980) for [OIII] 4959, (4990,5020) for [OIII] 5007, (6535,6556) for [NII] 6548, (6554,6572) for H α 6563, (6572,6600) for [NII] 6583, (6705,6724) for [SII] 6716 and (6725,6740) for [SII] 6731), and when assigning path to `save`, it will automatically save the image of each emission lines following the path.

We first find all the local maximums in the rough range, then pick out the one

with the most outstanding value, which is most likely to be the peak of the emission lines. After locating the peak, the standard deviation of the data within this rough range is calculated to decide whether the emission lines have a high signal-to-noise ratio (S/N). The program then checks whether the maximum value exceeds two and a half times the standard deviation. If it does not, it prints "low quality" and halts further integration. If the quality is sufficient, the program finds the first local minima on both the left and right sides of the peak, which define the intervals for integration.



After processing all the fits files with the program, we obtained data for each emission line associated with every planetary nebula (PNe) and generated visual representations of each emission line. I will review these images one by one to ensure that they are all fitted correctly. For situations where improvements required, such as under the cases of overlapping lines, I will remeasure to ensure the accuracy of the data.

	A	B	C	D	E	F	G	H	I	J	K
1	id	filename	H β 4861(4820,490	[OIII] 4959(4945,496	[OIII] 5007(4990,502	[NII] 6548(6535,65	H α 6563(6554,65	[NII] 6583(6572,66	[SII] 6716(6705,67	[SII] 6731(6725,6740)	
2	13790	309.8+00.5_MS	7.43E-15	1.06E-14	2.57E-14	8.91E-14	2.87E-13	1.44E-13	1.26E-13	1.34E-13	
3	13815	A48_MS110508	1.37E-14	1.61E-14	5.39E-14	1.67E-14	2.71E-13	5.30E-14	5.62E-15	4.79E-15	
4	9447	Alves1-cs_GT2	low quality	low quality	low quality	low quality	no observable line	low quality	low quality	no observable lines	
5	9448	Alves1_GT2108	2.23E-15	low quality	4.27E-15	low quality	2.73E-15	low quality	low quality	1.54E-16	
6	4303	bd30_N	No data	No data	No data	No data	No data	No data	No data	No data	
7	4304	bd30_OE	No data	No data	No data	No data	No data	No data	No data	No data	
8	4305	bd30_ON	No data	No data	No data	No data	No data	No data	No data	No data	
9	10545	BMP1209-5553	3.49E-15	1.95E-14	6.07E-14	low quality	5.67E-14	5.68E-16	3.01E-16	2.07E-16	
10	12980	Cn3-1_KP0408	1.26E-11	8.92E-13	2.76E-12	8.64E-12	4.15E-11	2.82E-11	8.89E-13	1.73E-12	
11	12981	DDDM1_KP210	1.64E-12	2.45E-12	7.46E-12	low quality	4.88E-12	9.31E-13	low quality	no observable lines	
12	5844	DSH_Kn15_WY	low quality	1.25E-14	low quality	low quality	low quality	low quality	low quality	low quality	
13	10382	ESO393-16_6D	170367.6048	667377.2436	98009.74519	388972.0093	low quality	895931.3132	42867.05697	82012.74377	
14	10527	ESO456-35_6D	291353.7503	1216.486516	1255.280548	634766.9165	2855773.271	1467015.56	79172.44429	154184.7824	
15	10529	ESO456-50_6D	1161075.234	4669.394306	8457.803091	no observable line	4354265.301	623975.7223	no observable lines	378779.2843	
16	10836	H1-39_BLUE_2	63293.98273	8393.777808	24441.25052	No data	No data	No data	No data	No data	
17	10837	H1-39_RED_2d1	No data	No data	No data	120978.3796	410953.9728	272148.8143	26044.83316	44515.60177	
18	10842	H1-43_BLUE_2	174792.7794	low quality	1330.420471	No data	No data	No data	No data	No data	
19	10843	H1-43_RED_2d1	No data	No data	No data	649059.2657	2858555.416	1898949.506	96606.63178	168385.5073	
20	10846	H1-47_BLUE_x_2	64670.23377	low quality	low quality	No data	No data	No data	No data	No data	
21	10847	H1-47_RED_2d1	No data	No data	No data	392517.856	935551.444	784025.3145	54954.15027	132397.3901	
22	4307	hb12_37E2S	No data	No data	No data	No data	No data	No data	No data	No data	
23	4306	hb12_37E	No data	No data	No data	No data	No data	No data	No data	No data	
24	4308	hb12_C	No data	No data	No data	No data	No data	No data	No data	No data	
25	12986	Hb12_KP01079	1.06E-11	1.74E-11	5.44E-11	2.34E-12	7.40E-11	6.79E-12	low quality	1.11E-13	
26	12987	Hb4_KP280603	7.97E-13	3.58E-12	1.13E-11	8.69E-13	7.99E-12	2.82E-12	1.56E-13	2.95E-13	
27	13001	He2-55_CT040	1.84E-13	5.50E-13	1.68E-12	no observable line	9.19E-13	low quality	7.70E-15	6.21E-15	
28	not found	21282_C	No data	No data	No data	No data	No data	No data	No data	No data	
29	not found	21282_L	No data	No data	No data	No data	No data	No data	No data	No data	
30	13004	IC1297_CT020	7.15E-12	3.28E-11	9.06E-11	no observable line	2.35E-11	4.22E-12	4.49E-13	5.98E-13	
31	13005	IC1747_AP080	8.77E-13	3.65E-12	1.12E-11	1.22E-13	4.52E-12	3.02E-13	2.02E-14	2.88E-14	
32	4311	ic2003	No data	No data	No data	No data	No data	No data	No data	No data	
33	13015	IC4776_CT020	1.63E-11	5.22E-11	1.49E-10	no observable line	5.65E-11	6.96E-12	4.02E-13	no observable lines	
34	13016	IC5217_KP010	5.69E-12	2.36E-11	7.16E-11	low quality	2.03E-11	1.77E-12	1.06E-13	low quality	
35	not found	IP185309+075	2.38E-15	low quality	low quality	1.05E-15	4.61E-14	3.40E-15	4.50E-16	5.06E-16	
36	5995	IP185309+075	2.38E-15	5.17E-15	1.73E-14	1.41E-15	5.02E-14	4.00E-15	5.78E-16	7.32E-16	
37	5614	IP185309+075	2.44E-16	low quality	low quality	low quality	low quality	low quality	low quality	low quality	

Part of table containing intensity of each emission lines

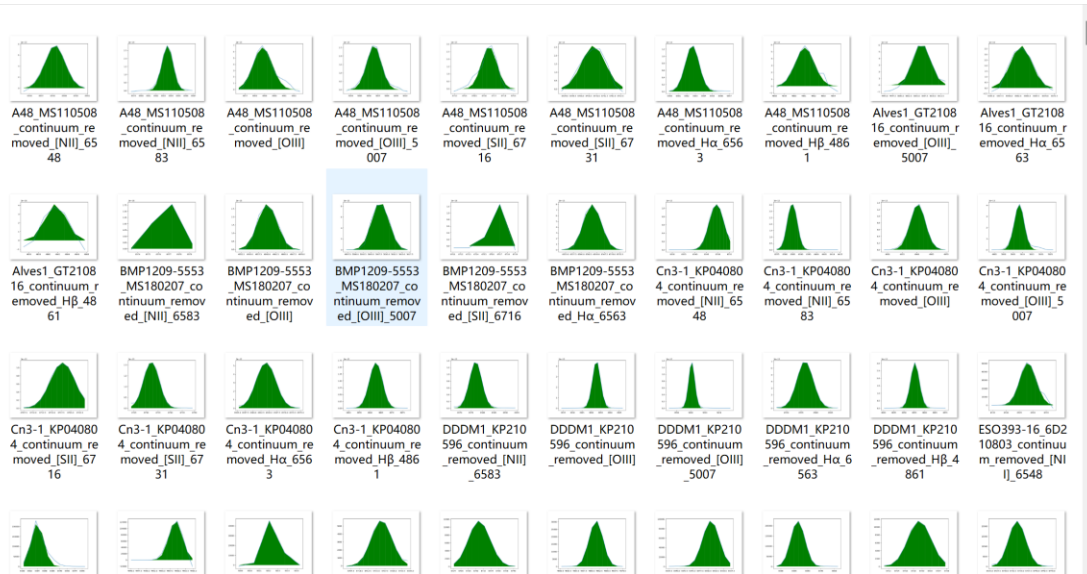


Image of different emission lines

Conclusion

In conclusion, this research significantly enhances our understanding of planetary nebulae and their central stars, particularly those exhibiting Wolf-Rayet features. By utilizing the HASH database and developing methods for precise emission line measurement, we identified several candidates for central stars of planetary nebulae. This work not only increases the catalog of known objects but also provides critical insights into the late-stage stellar evolution processes, contributing valuable data for future studies in astrophysics.

Future research will be crucial in advancing our understanding of the central stars of planetary nebulae. Expanding data analysis to include larger datasets will help identify additional candidates exhibiting Wolf-Rayet characteristics, enriching our catalog. Detailed spectroscopic studies of these candidates can refine their classifications and provide deeper insights into their evolutionary states. Additionally, developing theoretical models to simulate the late-stage evolution of these stars will contextualize our observations and enhance our understanding of stellar life cycles. Collaborative efforts with other research institutions could also foster knowledge sharing and lead to significant breakthroughs in the chemical processes driving stellar evolution.

Self-Reflection

As a passionate first-year student of physics, participating in a research project this summer was a significant milestone for me. This experience not only deepened my understanding of physics but also provided me with invaluable skills and insights that will shape my academic journey.

I realized that learning in a classroom is fundamentally different from engaging in actual research. I encountered numerous challenges. Among them, the most significant one is the limited knowledge I have gained after just one year of university study. Fortunately, my supervisor and mentor, Professor Parker and Dr. Ritter was incredibly patient and provided invaluable guidance for me throughout this process. As I navigated these challenges, I not only gained knowledge but also learned how to confront mistakes, challenge myself, and seek help when needed. This experience taught me the importance of resilience and adaptability in the face of obstacles.

Working alongside experienced physicists provided me with an authentic glimpse into the life of a researcher. Their dedication and focus were truly inspiring. I observed how they approached problems methodically, often spending hours refining their hypotheses and experiments. Witnessing their passion for discovery fueled my own enthusiasm and motivated me to adopt a similar mindset. I began to understand that being a physicist is not merely about mastering equations; it's about cultivating curiosity and resilience in the face of setbacks.

Throughout the project, I also learned the importance of perseverance. Research is inherently filled with uncertainties and obstacles, and it was easy to feel overwhelmed at times. However, I learned that every setback is an opportunity for growth. By maintaining a positive attitude and remaining committed to our goals, my team and I were able to navigate challenges effectively. This resilience is a lesson I will carry with me as I continue my studies.

In summary, my summer research experience at HKU LSR was transformative. I not only enhanced my technical skills, particularly in programming, but I also

grew as a leader and a collaborator. I came to appreciate the dedication and the importance of perseverance in research, which is needed to be a successful physicist. This journey has solidified my commitment to pursuing a career in physics, and I am eager to further explore the fascinating world of scientific inquiry. The skills and insights I gained during this summer will undoubtedly serve as a strong foundation for my future academic endeavors.

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