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Planetary Nebulae
NGC 1514 – NGC 40

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Abstract

This project compares two planetary nebulae (NGC 1514 and NGC 40) and studies the difference between them in their chemical composition. Observations of the two planetary nebulae were done at Clanfield Observatory with the 24-inch Ritchey-Chrétien telescope. This project found that both planetary nebulae have a similar nebula spectrum but a different central star spectrum. The NGC 1514 central star is a type 'DA white dwarf'. While the NGC 40 central star is a type 'DQ white dwarf'. The different classes of white dwarfs could be a result of AGB thermal pulsations or superwind phases.

Keywords – Planetary Nebulae, White Dwarfs, Chemical Composition, Stellar Evolution, Galaxy Evolution, Astronomical Spectroscopy, Emission Lines.

1. Introduction

By looking at the sky, there are billion trillions of stars. At some point, each one of these stars became an individual and they have their own identity [1]. When an intermediate-mass star (between 0.5 and 8 solar masses) sheds its outer layers into space at the end of its life, leaving the core remnant which is a White Dwarf (WD), and forming a region of cosmic gas and dust which is called a Planetary Nebula (PN) [2]. As shown in Figure 1, planetary nebulae have different shapes and colours depending on many different factors such as magnetic fields, gravitational interactions, and chemical compositions [2].

During the main sequence of an intermediate-mass star, hydrogen is converted into helium in it is core [3], and the star is in hydrostatic equilibrium which means the star is stable due to a balance in the gravitational force and the gas pressure as described in Equation 1 [4]. When the core of the star runs out of hydrogen, the hydrostatic equilibrium breaks and the core contracts. While the outer layer of the star which is mostly hydrogen expands, cools and glows red while expanding, this is called the red giant phase. The nebula expands due to radiation resulting from rising the core's temperature. At this stage, the core fuses helium into carbon and other elements such as oxygen. However, the lowest-mass stars do not go under this process and never burn helium into carbon. After that, the core collapses again and the outer layers are expelled forming a PN [4]. The core becomes a white dwarf which is a dense ball of carbon and oxygen, with a temperature that can exceed 100,000 Kelvin [5]. The life cycle of a star is shown in Figure 2 [6].

This project aims to compare two planetary nebulae (NGC 1514 – NGC 40), to determine some of the differences in the physical characteristics such as the chemical composition. Also, this project will connect PNe to galaxy evolution as PNe contribute significantly to the chemical evolution of the galaxy by dumping material back into the interstellar medium [2].

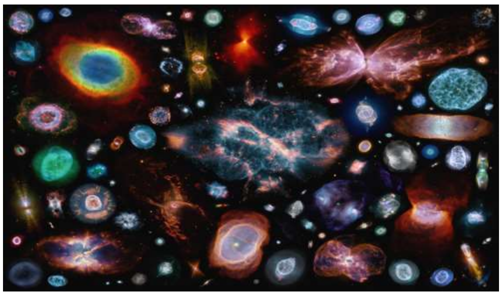

Figure 1. 99 PNe of different shapes and colours Credit: Hubble / ESA / NASA; processed by Judy Schmidt.

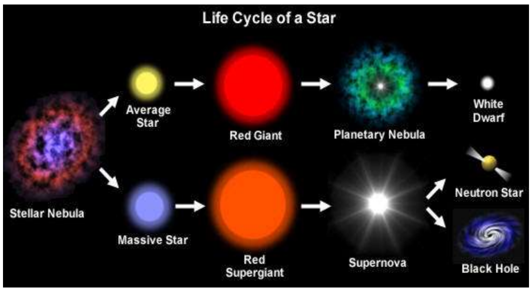

Figure 2. The life cycle of a star. Credit: NASA.

2. Theory

As mentioned above, when the star is in hydrostatic equilibrium, the gravitational compression force acting on the mass is balanced by the outward pressure force, resulting in $dF_g + dF_P = 0$, and the hydrostatic equilibrium can be described by Equation 1 [7].

$$\boldsymbol{\frac{dP}{dr} = -\frac{G\,\rho(r)m(r)}{r^2}} \tag{1}$$

Where $\boldsymbol{\frac{dP}{dr}}$ is the change in pressure with respect to the radius, $\boldsymbol{G = 6.6743 \times 10^{-11} m^3 kg^{-1} s^{-2}}$ is the gravitational constant, $\boldsymbol{m(r)}$ is the mass of the star, $\boldsymbol{r}$ is the radial distance, and $\boldsymbol{\rho(r)}$ is the density of the gas.

Also, as it is about to be specified later, planetary nebulae shine due to the gas atoms within them emitting light. Planck's law can be used to calculate the energy of a photon emitted due to electronic transitions within an atom as shown in Equation 2. This energy is related to the wavelength ($\boldsymbol{\lambda}$) of the emitted photon and the energy difference ($\boldsymbol{\Delta E}$) between two energy levels within the atom [8].

$$\boldsymbol{E = hv = \frac{hc}{\lambda} = \Delta E} \tag{2}$$

Where $\boldsymbol{h = 6.62607015 \times 10^{-34} m^2 \frac{kg}{s}}$ is Planck's constant, $\boldsymbol{c = 299\,792\,458 \frac{m}{s}}$ is the speed of light, and $\boldsymbol{v}$ is the frequency of the emitted photon.

2.1 NGC 1514 – NGC 40 Background Information

This project is a partnership with Clanfield Observatory, and all the observations were taken by the 24-inch Ritchey-Chrétien telescope as shown in Figure 3. The main focus was to observe two planetary nebulae (NGC 1514 – NGC 40). These two Planetary Nebulae were chosen depending on many factors, such as brightness which they need to be bright enough to get the spectra in a reasonable time, position in which they need to be observable during the project period, and size which they have to be a suitable size, not too big so we cannot separate the background from the nebula and not too small to be faint and to be unable to separate the spectra of the WD and the nebula.

The NGC 1514 also known as The Crystal Ball Nebula, is located close to the Perseus border in the constellation Taurus. It has an apparent magnitude of 9.43 and lies at an approximate distance of 2,200 light-years (700 parsecs) from Earth. It occupies an area of 2.2 arc minutes [9].

However, the NGC 40 which is known as The Bow Tie Nebula, is located in the northern constellation of Cepheus. It has an apparent magnitude of 10.7 and lies at an approximate distance of 3,500 light-years from Earth. It has a radius of 0.30 light years and an age of 4,500 years [10].

2.2 Connection between Planetary Nebulae and Galaxy Evolution

The lifetime of planetary nebulae is short compared to the lifetime of the original intermediate-mass star, which shines for thousands of millions of years; they only last for a few thousand years [11]. As the nebula expands, all the gases continue to move away from the central star (WD) until they dissipate. At this point, all the gases become part of the interstellar medium, which forms a recycling loop. Therefore, planetary nebulae play a crucial role in forming the next generation of stars. The nebula gases have a high metallicity which is the fraction of heavier elements, and the stars formed from those gases will also have a high metallicity [12]. Astronomers define metals as all the elements other than hydrogen and helium [13].

Figure 3. The 24-inch Ritchey-Chrétien telescope. Credit: Hampshire Astronomical Group.

3. Observations

As mentioned above, all the observations were made in Clanfield Observatory. There were two main goals of the observation. The first goal was to get clear pictures of the two planetary nebulae. Where the second goal was to produce the spectra for the whole system of the two Planetary Nebulae (WD and PN). To achieve these two goals, the following steps were made.

First, the 24-inch Ritchey-Chrétien telescope and the dome were set up. A Canon camera (5D Mk II) was attached to the telescope to capture some images of the planetary nebulae. The telescope was pointed at the first target which is NGC 40. By using the camera, 10 images of the NGC 40 were taken with an exposure of 1 minute per image. The background of the images was so bright because of the full moonlight. Second, the Canon camera was taken off to put the Shelyak Lhires spectrometer in place in order to get the spectra of the NGC 40 nebula and WD. After adjusting the WD to be in the right position, which is the center of the screen as shown in Figure 6, the spectrometer started to take the spectra. The spectra were taken 10 times with an exposure of 2 minutes per spectrum, to obtain an average which led to a better signal-to-noise ratio and a better result. The signal-to-noise ratio varies across the spectrum as the instrument response varies with wavelength. All the images and spectra were stacked together using the StarStax software. For stacked image sets the signal-to-noise ratio decreases with the square root of the number of stacked images.

The same process was made for the NGC 1514, but with longer exposure of 5 minutes per spectrum, to get more details as the NGC 1514 is much fainter than NGC 40 and there was a light cloud in the way. The spectrum was taken 5 times to get the average spectrum. Third, a calibration spectrum was made from a Neon/Argon lamp that is in the spectrometer itself, to help identify all the spectrum lines with their wavelengths and use it as a reference spectrum as shown in Figures 4 and 5. Finally, after collecting all the data, the Rspec software was used to analyse the data. Figures 6, 7, and 8 show some snapshots of the software and programmes that were used. For example, the left part of Figure 6 shows the auto-guider software called (PHD2) and the star locked in the correct position, while the right-hand part shows the camera software called (ASIimg). Also, the top left part of Figure 7 is the manual control for the telescope, the right-hand map is the star chart used to find the target, and the bottom left side is the dome controller.

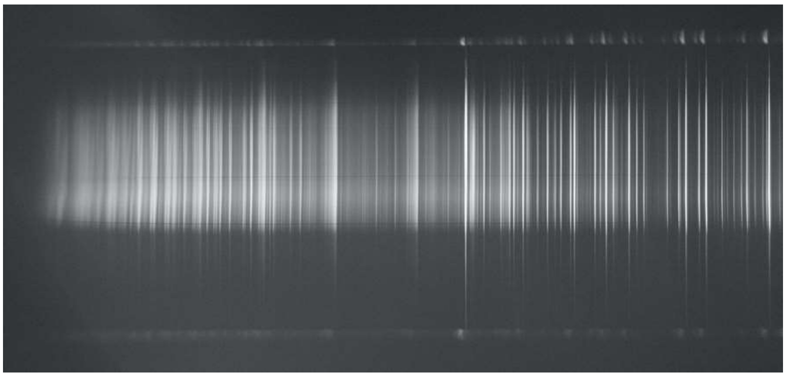

Figure 4. The calibration spectrum (Neon/Argon lamp).

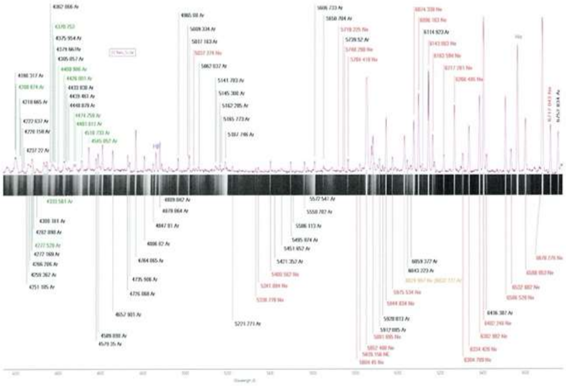

Figure 5. The calibration spectrum with all the wavelengths identified.

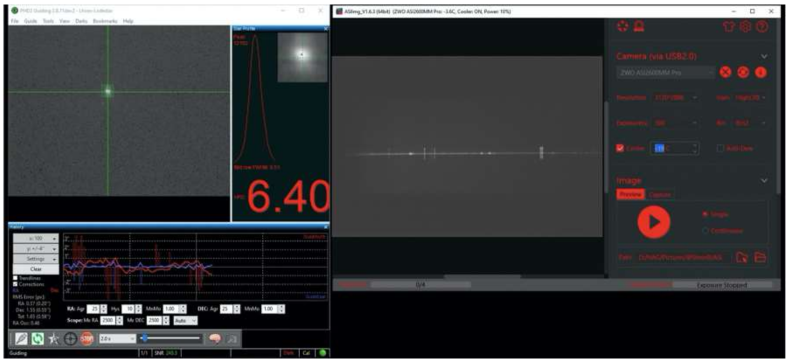

Figure 6. A snapshot of the camera software (ASIimg) shows the NGC 40 spectrum.

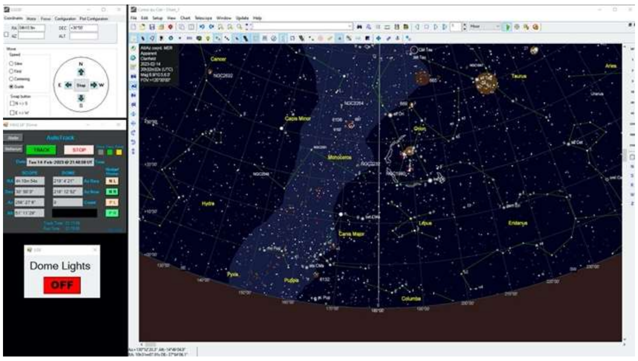

Figure 7. A snapshot of the telescope software (Cartes du Ciel) and the dome controller.

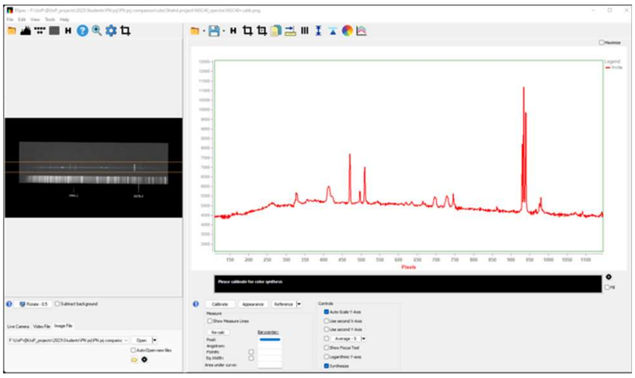

Figure 8. A snapshot of the Rspec software where the data was analysed.

4. Results

4.1 NGC 1514

After taking 10 pictures of the NGC 1514, all the pictures were stacked together using StarStax software to remove the background noise and to get the best result as shown in Figure 9. Moreover, after having the spectra for the NGC 1514 (nebula and WD), the Rspec software was used to produce, separate, and analyse the spectra. The first step was to separate the spectrum of the nebula and the spectrum of the WD to study more details about the system. The spectrum of the whole system is a combination of the spectrum of the WD which is a continuous spectrum with absorption lines [14], and the spectrum of the nebula which produces emission lines resulting from energetic photons radiated from the central star (WD) that excite the atoms in the nebula, which make the atoms in the nebula ionized [15]. The energy of the emitted photon can be described by Equation 2. As shown in Figure 10, the white horizontal line is the WD spectrum, and the vertical lines are the nebula emission lines. The long vertical line at the middle of the spectrum is light pollution. By fixing the two yellow horizontal lines as shown on the left side of Figure 8 between the emission lines, the spectrum of the nebula can be produced individually. Moreover, by subtracting the original spectrum from the nebula spectrum, the WD spectrum can be produced.

The next step is to use the calibration spectrum to convert the x-axis of the NGC 1514 spectra from pixels to wavelengths. The conversion can be made by identifying two lines with their correct wavelengths in both spectra (calibration spectrum and the NGC 1514 spectrum). At this stage, the spectrum of the NGC 1514 nebula and the spectrum of the NGC 1514 WD are ready for the analysis.

As shown in Figure 11, the spectrum of the NGC 1514 nebula shows an emission line of hydrogen alpha [$\mathbf{H_\alpha}$] which is at 6563 Angstroms [**Å**] and two emission lines of oxygen three (doubly ionized oxygen) [**O[III]**] at 4961.0 **Å** and 5007.5 **Å** with wavelength accuracy of + or – 1.3 **Å**. This spectrum was expected as the typical spectrum of a nebula can show emission lines of hydrogen, helium, oxygen, nitrogen, and other elements [16].

As shown in Figure 12, the spectrum of the central star (WD) of the NGC 1514, shows hydrogen absorption lines. The first two absorption lines from the right side which represent oxygen [**O**] and water [$\mathbf{H_2O}$] are from the Earth's atmosphere. The emission line of oxygen three [**O[III]**] which is at 5007.5 **Å** is from the nebula as we need to look through the nebula to see the WD. The majority of the WDs (two-thirds of the total number) display only pressure-broadened hydrogen absorption lines in their spectra, like the NGC 1514 WD and this group is called 'DA White Dwarfs' [17]. The strong gravity of the WD pulls heavier elements below the surface towards the core, while the lighter hydrogen rises to the top, resulting in a thin outer layer of hydrogen covering a layer of helium on top of the Carbon-Oxygen core, and that explains the DA White Dwarfs spectra [17].

Figure 9. The NGC 1514 PN.

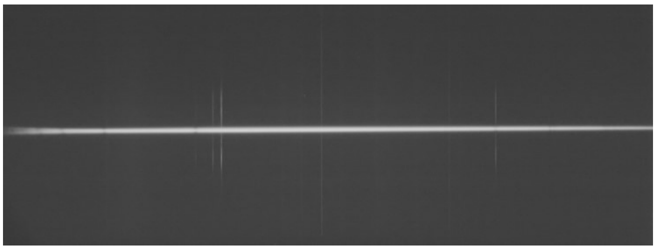

Figure 10. The NGC 1514 spectrum (both the nebula and the WD). The x-axis which is the horizontal line shows the WD spectrum with absorption lines. While the vertical lines on the y-axis show the emission lines coming from the nebula. The central vertical line is light pollution.

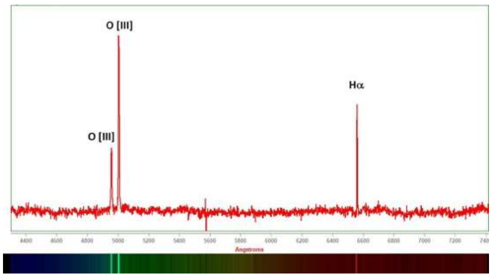

Figure 11. The NGC 1514 nebula spectrum showing hydrogen and oxygen emission lines. Where the x-axis is the wavelengths, and the y-axis is the relative luminosity with arbitrary units.

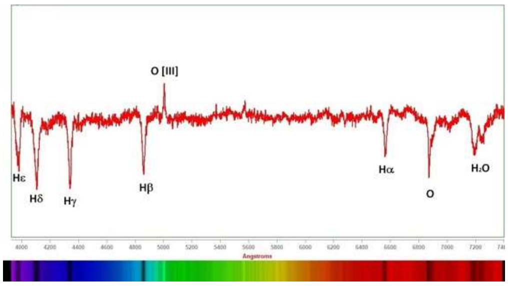

Figure 12. The NGC 1514 WD spectrum showing only hydrogen absorption lines.Where the x-axis is the wavelengths, and the y-axis is the relative luminosity with arbitrary units.

4.2 NGC 40

All the images of the NGC 40 taken by the telescope, were stacked together by using StarStax software to get the best result as shown in Figure 13. The same process and equipment were used to generate the spectrum of the NGC 40. After producing the spectrum of the NGC 40 (the spectrum for both the nebula and the WD), a conversion to the wavelengths on the x-axis was made by identifying two lines with their correct wavelengths in both spectra (calibration spectrum and the NGC 40 spectrum) as shown in Figure 14. In Figure 14, it is noticeable that the nebula has vertical emission lines and the WD is the horizontal line. By using the Rspec software and the same steps that were made to separate the NGC 1514 spectra, the two individual spectra of NGC 40 (the nebula and the WD) were produced.

As shown in Figure 15, the spectrum of the NGC 40 nebula displays hydrogen, oxygen, and nitrogen emission lines which was expected as the spectrum is similar to a typical nebula spectrum as mentioned above. The main difference between the NGC 1514 nebula spectrum and the NGC 40 nebula spectrum is that the NGC 40 nebula spectrum shows nitrogen emission lines while the nitrogen is missing in the NGC 1514 nebula. Chemically speaking, planetary nebulae are enriched in elements created by nuclear fusion inside the central star [18].

The spectrum of the NGC 40 WD was surprising and unexpected. As shown in Figure 16, the spectrum of the NGC 40 WD displays emission lines of carbon, helium, and oxygen which is similar to the Wolf-Rayet (WR) star spectrum as shown in Figure 17. A Wolf-Rayet star is a massive star losing it is mass at a late stage of stellar evolution [19]. There was confusion if this is a WR star or a WD. After doing some research, it turned out that this is a type of WD, and it is spectrum looks similar to a WR star but with some differences. For example, the spectrum of the WR star has broader emission lines because of having a higher temperature. Research shows that 5-6% of the PNe central stars are hydrogen-deficient and show emission lines in their spectra [20]. Half of these hydrogen-deficient stars have spectra similar to those of massive Wolf-Rayet stars of the carbon sequence and are therefore classified as spectral type [WC] (the square brackets were used to distinguish between the WD and the WR star [20]). They have a strong stellar wind composed of helium, carbon, and oxygen [21]. As the NGC 40 WD shows carbon features in their spectra, they are classified as 'DQ White Dwarfs' type [17]. The reason for the origin of the non-DA white Dwarfs is not clear yet. However, the thermal pulse during the Asymptotic Giant Branch (AGB) or the superwind phases may strip off almost all the hydrogen from the WD [17].

Figure 13. The NGC 40 PN.

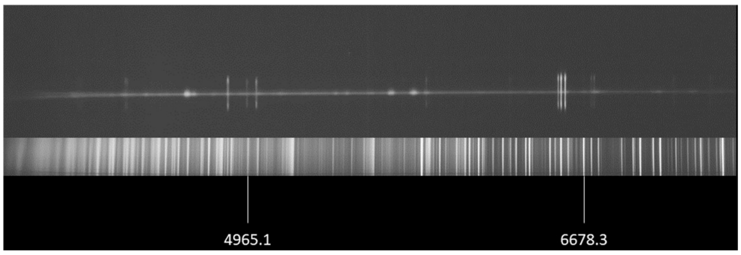

Figure 14. The NGC 40 spectrum (top). The calibration spectrum (bottom). In the NGC 40 spectrum, the horizontal line shows the WD spectrum with emission lines. While the vertical lines show the emission lines coming from the nebula.

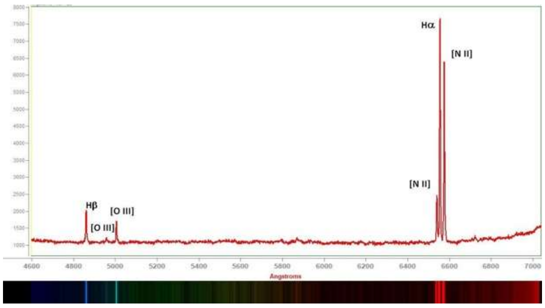

Figure 15. The NGC 40 nebula spectrum showing hydrogen, nitrogen, and oxygen emission lines. Where the x-axis is the wavelengths, and the y-axis is the luminosity.

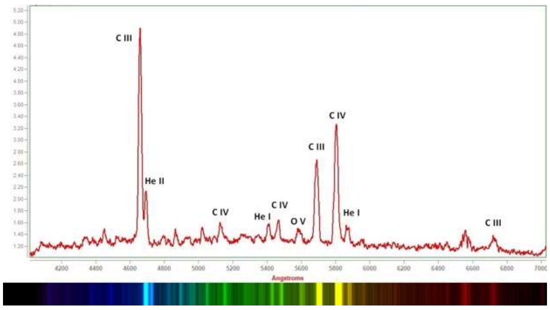

Figure 16. The NGC 40 WD spectrum showing carbon, helium, and oxygen emission lines. Where the x-axis is the wavelengths, and the y-axis is the luminosity.

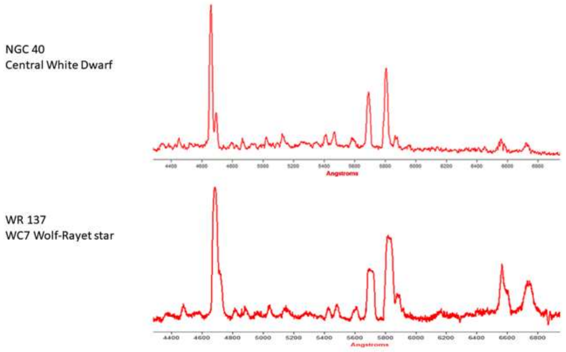

Figure 17. A comparison between the NGC 40 WD spectrum (top), and the WR star spectrum (bottom).

4.3 Limitations and further developments

The original aims of the project have been met to a high extent as a comparison between NGC 1514 and NGC 40 spectra was done. There were some limitations and factors that affect the observations, such as bad conditions which involve light clouds and a full moonlight. This project can be carried out further to compare and analyse more PNe spectra to discover the differences in the chemical compositions and the types of WDs.

5. Errors

This project may have some errors in the observations and data due to different factors. For instance, bad conditions such as full moonlight or light clouds could affect the images taken by increasing the noise in the background or adding some elements to the spectrum as we saw the $[\mathbf{H_2O}]$ in the NGC 1514 WD spectrum. Also, because all the observations were done with a ground-based telescope, atmospheric disturbance may occur. In addition to that, if the targeted object is faint and not very bright, it can make the observations much longer. Moreover, as spectroscopy is sensitive to light, any sort of light inside the dome may affect the results.

The results can be more accurate in many different ways. For example, repeating the observations many times on separate days. As well as taking long exposure for the images and the spectra to get more details. Furthermore, observe more similar objects (more PNe) to compare the results.

6. Conclusion

The main goal of this project was to compare two planetary nebulae (NGC 1514 and NGC 40) to determine some of the differences in the physical characteristics such as the chemical composition. This aim was achieved by observing the two planetary nebulae, collecting the data, and analysing the results. The spectra for both the nebula and the WD were produced for both of the planetary nebulae.

There were two main results of this project. The first result was that the NGC 1514 and the NGC 40 have similar nebulae spectra but with completely different WDs spectra. The NGC 1514 nebula spectrum shows hydrogen and oxygen emission lines. However, the NGC 40 nebula spectrum shows hydrogen, oxygen, and nitrogen emission lines. The second result was that there are different types and classifications of the central star (WD). According to [17], there are five classes of WDs. DA white dwarfs, DB white dwarfs, DC white dwarfs, DQ white dwarfs, and DZ white dwarfs. Two of these classes were mentioned in this project. The NGC 1514 central star displays hydrogen absorption lines in it is spectrum which is a DA white dwarf. While the NGC 40 central star displays carbon features in it is spectrum which classifies it as a DQ white dwarf. The spectrum of the NGC 40 WD was similar to the WR star spectrum.

There were some limitations due to the bad weather, but the observations were done, and the results were generated. This project can make an impact on different topics in physics such as Steller Evolution, Galactic Evolution, and Steller Remnants. Also, this project can help in understanding the different classes of the white dwarfs with some examples. Finally, this project can be taken further for a better understanding of the above-mentioned study areas.

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