Astrophysical Modeling of Wolf Rayet Stars Using Low Resolution Gratings

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Abstract

Wolf Rayet (WR stars), which are poorly studied in the field of astronomy, are massive stars with luminosities a million times bigger than the Sun's and temperatures about 8 times higher. It's also known that WR stars have an emission maximum in the UV area and that they are old stars, meaning that they present a different behavior in HR diagrams. Usually, research regarding stars such as this is conducted by professional astronomers with access to instrumentation with the latest technology. So, we wondered if high school students could make progress in this field of study with such scarce resources and, if so, what methods could we use. Our project consists in an integrated investigation of several WR stars, resorting to visible spectroscopy and using low resolution gratings, to study some of their astrophysical parameters. By using spectral data recovered from "on site" observations and from observations made on a small regional observatory, with resort only to freeware for data reduction, we were able to obtain accurate results for temperature, radius, stellar winds and chemical composition which suit the predicted data from the literature. All this data confirmed the current WR star models and even added some information about the astrophysical dynamics of WR stars throughout time, such as their intrinsic behavior and how they interact with their interstellar medium. Due to this project, we did reliable scientific investigation which we hope is going to be important to astronomy studies in the future.

1. Project General Description

The project "Astrophysical Modulation of Wolf Rayet stars using low resolution gratings" was developed by a group of pre-college students from the scientific-humanistic courses in D. Maria II Secondary School, in Braga, in direct collaboration with the University of Porto's Astrophysics Center and the University of Minho's Physics Department.

This research intends to be an innovative way to approach the spectroscopy of Wolf Rayet stars, which have their emission peak in the ultraviolet region, by using low cost and low resolution gratings to retrieve data from the visible and near ultraviolet range. All the data was retrieved in observatory environment, by the students integrating this research, was requested to fellow astronomers and was compared with international data published in several papers. Our data was simultaneously shared with the astronomers that cooperated with our team and agreed to provide assistance in the learning process, using their work typology.

Our research presents innovations in terms of approach, data collection and data comparison. The fact that we used comparison data ranging from 2011 to 2015 allowed us to take some conclusions about the stellar dynamics, during this time interval, of these stars that are considered to be one of the strangest celestial bodies in the observable universe.

2. Objectives

This research involves, at its genesis, an innovative approach to high temperature star spectroscopy, using tools and equipment accessible in schools, so that students can be able to modulate stars like the Wolf-Rayet type and discover, through spectral analysis, some enigmas that are still unresolved. It's good to remind that, besides being part of the curricular programs on Physics and Chemistry disciplines, spectroscopy is given to students in an abstract way and almost none of the students are able to recognize its true potential. So, another objective is to reach out to students and demonstrate that spectroscopy is accessible and has a vital importance in modern day science. It's actually the only way astronomers have to study what otherwise would be inaccessible, the stars.

By using visible band spectra we analyzed a star type with its emission peak in the ultraviolet band, we are innovating by using a study method different from usual. Also, by using low aperture telescopes and low resolution spectrographs and gratings, we enter a complete new approach in astronomy – the notion that making science, namely astrophysics, is not only for scientists with millions in equipment at their disposal. Normally, the instruments used by astronomers in this type of tasks usually costs between 10.000 and hundreds of thousands of euros/dollars.

We intend to prove that, with this approach, scientific research with low cost instruments can lead to good results and conclusions, close to the ones taken by professional astronomers. Besides that, we want to contribute to the enlargement of the actual knowledge about WolfRayet stars and, at the same time, perceive the world of scientific research and be a part of it.

3. How to obtain data from celestial bodies

As we all know, the Moon is the only celestial body ever visited by mankind. As a result of those visits, several samples were brought back to Earth, such as lunar rocks, for further analysis. Those samples contributed to the knowledge about the Moon's geological proprieties. However, our knowledge of the celestial bodies in the universe is not restricted to the Moon. We know a lot about our Sun, about the planets in the solar system, stars, galaxies, and even about the initial moments of the universe. So, if we cannot physically visit these celestial bodies, how do we acquire such information? We all heard that the Sun is basically composed of hydrogen and helium and that its surface it's "boiling" around 5800K (5527ºC/9980ºF). However, how do we know such thing if we never been there?

The answer lies in light that reaches the Earth coming from everywhere in the universe, all kinds of electromagnetic radiation that reaches us, from it we can extract a lot of information. Actually, everything we know about all bodies beyond the solar system, as well as the region of the universe where they are located, results from the study and analysis of the proprieties that light contains.

4. The electromagnetic spectrum

When we look at a luminous object, we can obtain information about its brightness, its color, and eventually its shape. But is there any "hidden" information in the light that we capture? If we grab a CD disk and look at the light that is reflected by it, either solar light or from a lamp, we can observe a set of colors similar to what we observe in a rainbow. But where do those colors come from? Although the rainbow phenomena is known since the beginnings of humanity, it was only experimentally and systematically studied after 1666, by Sir Isaac Newton (1643-1727), a British physicist considered one of the most influential scientists in modern science.

When light emitted by any body passes through a glass or acrylic prism or, more usual this days, through a diffraction grating, the light decomposes (separates) into the colors that compose it. That sequence of colors is then designated by spectrum. Different colors correspond to different values of a very important characteristic of light: its frequency. In any situation, light or any kind of electromagnetic radiation acts as a wave. In other words, it's a periodic wave phenomenon. That periodicity can be explained as frequency, which, by itself, means the number of complete oscillations per unit of time.

Allied to the frequency comes another wave characteristic, wavelength, that corresponds to the distance between two consecutive and equal phases of the wave's vibration. Frequency and wavelength are directly related by the wave's velocity, given by the equation:

$$v = \lambda \cdot f \qquad (1)$$

in which v is the wave's velocity, λ is the wave's wavelength and *f* is its frequency.

When we look into a spectrum, a different color shades that correspond to our eye's detection of light has different frequencies, that is, different wavelengths [1]. Therefore, radiation with wavelengths in the order of 400 nm is seen as blue light and, as wavelength grows larger, we perceive several colors until we reach red colors at around 610-700 nm. The result is a continuum spectrum of light and colors.[1]

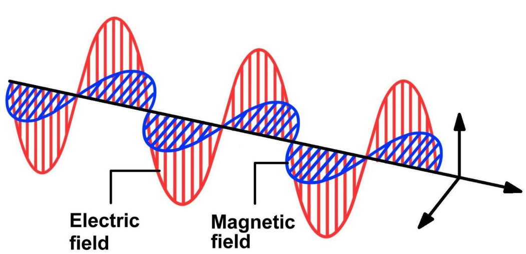

Figure 1: Scheme of an electromagnetic wave. The wavelength is the distance between two consecutive and equal phases of the wave's vibration.

Beyond these extremes we find, e.g. ultraviolet and infrared radiations that we cannot see. This sequence of radiations, where wavelength come in crescent order and frequency comes in decrescent order, is called electromagnetic spectrum.

5. Types of spectra

Figure 2: Emission spectrum. This type of spectrum is easily identifiable because it presents a dark background with emission lines of different colors. This figure represents the emission spectrum of air.

Figure 3: Absorption spectrum. This type of spectrum presents dark lines over a colored background made by a continuous spectrum. This figure represents the absorption spectrum of hydrogen.

The spectra that we observe when light from different bodies is decomposed are not the same. We cannot always see a continuum of colors with smooth transitions from one color to another. Instead, we occasionally see some colored lines but, eventually, we se a continuum of colors and some dark lines. These colored lines are associated to emission spectra and the dark lines are present in the absorption spectra.

When the light comes from a light emitting body the spectrum is a emission spectrum, when it comes from a illuminated body, the spectrum is a absorption spectrum.

Spectra contain much of the information that comes to us from the outer space. This information comes from continuous and discontinuous spectra . This latter class of spectra is particularly useful because it allow us to identify different chemical species.

[1]Strictly speaking the sensation of color depends simply on frequency, since wavelength can vary depending on the environment it travels . However, its more usual to refer to color in terms of wavelength. In this case, wavelengths refer to the light's propagation through space, through vacuum or through air, where, according to Snell-Descartes laws of diffraction, the velocity of light is practically the same.

[2]Continuous spectrum if we ignore Fraunhöfer lines

The study of discontinuous spectra began carry out a project that had a link o the interin the XIX century when the study of spectra national year of light. Since spectroscopy is the from gases began. When enclosed inside a separations of light to analyze the characterislight bulb, these gases glow if an electric cur- tics of a star, we found a good chance to achieve rent passes through them. When we compare that. Next, we will show some examples that the spectra emitted by the ampoule's light and indicate what we can learn by studying the the solar spectrum[2] we found that, unlike the light that reaches us from the stars. sun's spectrum , the gas spectrum has a series of colored stripes on a dark background and not a continuous spectrum.[1]

6.1. Chemical Composition

It was also found that ampoules with dif- It was already mentioned that different chemferent gases emit different spectra. This was a ical elements present a different spectrum. very important discovery, because it results From analyzing a star light spectrum we can from a fact that is the basis of all interest identify chemical elements that contribute to its in spectroscopy: each chemical element has emission/absorption. This way, we can learn is own spectrum, being different from all about the chemical constituents of the universe. the other elements spectra. This phenomena Same way, the spectrum analysis of a star alstarted a new science and investigation, culmi- lows us to know which are the chemicals that nating into a new model for the atom. In fact, compose it.

the only explanation for this phenomenon was By studying the spectrum of a planet we to consider that the atom's energy was quan- gain information about the chemical compo tified, an idea that hitherto didn't made much sition of its atmosphere. Similarly, a spectral sense.[2] analysis of a star allows us to determine the chemical composition of its surface and atmo-

6. Light and its importance

sphere. This technique also allows us to know the chemical composition of nebulae and galax- ies.

Unlike what happens in other sciences, such as physics or chemistry, were we can manip- It is important to note that the existence of ulate and control laboratory experiments, in certain spectral lines does not rely only on the astronomy we cannot touch or manipulate the presence of the chemical element that causes it. objects of study. The light that comes from The ambient temperature that causes the specspace plays an important role in astronomy. trum is also a determining factor for the presExcluding some samples of lunar rocks col- ence or absence of certain lines in a spectrum, lected by Apollo missions and analyzes made it is from this lines that we find the chemical by some space probes sent to some planets in composition of a certain star.

[1] This can also be achieved, for example, from an incandescent lamp.

[2] More information on the quantification of energy in the atom can be found in any Physics and Chemistry book

the solar system, everything we know about Thus, it is possible that a certain element the universe comes from the light that reaches is present in the environment that produces us. a given spectrum, but its presence is not dis-

Furthermore, the United Nations General closed in the spectrum. Assembly proclaimed 2015 as the International Year of Light. By proclaiming an International

6.2. Temperature

Year focused on optical science and its applications, the United Nations recognize the im- Scientists from century XIX found that the inportance of global awareness of technologies tensity of radiation at each wavelength is in based on light. function of the emitter body's temperature. A

Our project recognizes the importance of warm body emits radiation with higher frelight as the foundations of all the concepts stud- quencies, that is, lower wavelengths, related ied in astronomy. We also found important to with colder bodies. For example, in Figure 1,

curve shows the radiation emitted by an object at three different temperatures.

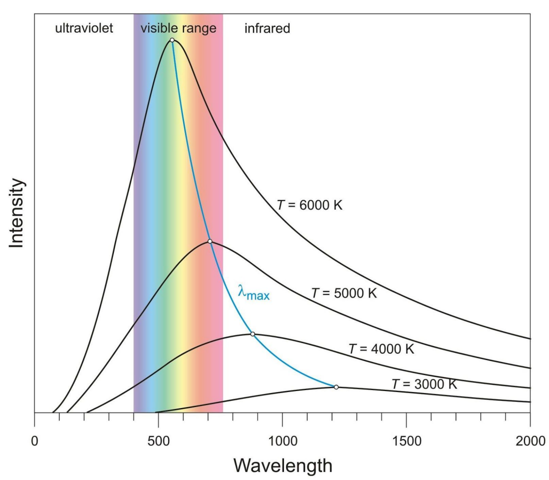

Figure 4: A blackbody radiation as a function of wavelength for four different temperatures. In this figure we use Kelvin as units of temperature. Note that 0^{o}C=273,1K

We can see that at the lowest temperature (3000 *K*) the object emits more energy (it's brighter) when the wavelengths are closer to 1250 *nm* . An object at the temperature of 4000 *K* is brighter at around 900 *nm*, an object at the temperature of 5000 *K* is brighter when its radiation wavelength is slightly shorter than 700 *nm* and an object at the temperature 6000 *K* is brighter when its radiation wavelength is around 550 *nm*.

By applying this knowledge directly to the stars we can, indirectly, determine the temperature at its surface. In this case temperature is determined from the continuous spectrum emitted by te star.

The most common form to estimate stars temperature is from lines that are present in its light absorption spectrum. The absorption line intensity of a certain chemical elements species on the temperature at which they are formed. For example, a star that presents lines that are characteristic of He+ (helium atom with one electron removed) is a very hot star with temperatures in the order of 30, 000◦.

On the other hand, if the star has intense lines of titanium oxide (TiO), it is a sign that the star is cold with surface temperatures around 2500◦ C. Between these two extremes lie other stars with intermediate temperatures and with different intensities for different absorption lines. For example, stars like the sun have an intense Ca + (calcium atom with one electron removed) absorption line.

However, there are also alternative mathematical methods to determine the temperature of stars.

One of them is the application of Wien's displacement law. Once the star spectrum is extracted and analyzed, by software we can get its Plank curve. Afterward, we can calculate the star surface temperature *T* by Wien's Law:

B

$$\lambda_{max} = \frac{B}{T} \quad (2)$$

$$T = \frac{B}{\lambda_{max}} \quad (3)$$

where λ_{max} its the wavelength corresponding to the maximum value of the Plank curve and B is Wien constant, with the value $2,9878 \cdot 10^{-3}$ m K.

For example, if the maximum wavelength is 480 mn ($4,8 \cdot 10^{-7}$ m), we have:

$$T = \frac{2,898 \cdot 10^{-3}}{4,8 \cdot 10^{-7}} \quad (4)$$

$$T \simeq 6000K \quad (5)$$

Another method would be the implementation of the Stefan-Boltzmann's law (though we don't use it along this paper). Starting from its main statement: The thermal energy radiated by a blackbody radiator per second per unit area is proportional to the fourth power of its absolute temperature.

From this, we deduce the temperature expression:

$$I = \sigma T^4 \quad (6)$$

$$T = \sqrt[4]{\frac{I}{\sigma}} \quad (7)$$

where I is the total intensity emitted by a black body (perfect radiation emitter and absorber) and σ is the Stefan-Boltzmann constant, $5,67 \cdot 10^{-8}$ W $m^{-2} K^{-4}$

For example, knowing that a body emits radiation of $7,35 \cdot 10^{7}$ W m^{-2}, we have:

$$T = \sqrt[4]{\frac{7,35 \cdot 10^{7}}{5,67 \cdot 10^{-8}}} \quad (8)$$

$$T \simeq 6000K \quad (9)$$

6.3. Temperature Determination

As for determining the temperature we faced a limitation. For stars with temperatures above 9000 K it is not possible to observe the peak in the curve, necessary in Wien Law method. This peak is outside the visible spectrum in the ultraviolet region, so we are not able to determine its wavelength. The same goes for lower temperature peaks where the star's spectrum peak is in the infrared region of the spectrum and therefore, it is also outside the visible spectrum.

In such cases we could only use the Planck curve to determine the peak emission. Unfortunately, this method was also proved fruitless, because of the relative error that this method produces in WR stars. Summing up, you can not apply these simple methods to determine the approximate temperature. So we were forced to do a much more complex approach.

One of the must important parameters in stellar astrophysics is the determination of an effective temperature, therefore the determination of the temperature became vital to our final result.

This is the most difficult parameter to measure with precision, especially for stars that are not closely related to our own star, the sun. This parameter has a great effect on the determination of other associated parameters, such as gravity on the surface and the chemical composition of the studied star.

There are several other methods to determine the effective temperature of stars. One of them is a photometric method, it is based on the calibration of multiple bands such as (B - V), (b - y), (V - K), etc. (E.g. *Nordström et al 2004*). As we are using spectra, the method that seemed the most obvious was to try to get the temperature from the spectrum. This technique is apparently very powerful to determine the effective temperature if we make a very careful analysis of the spectra along with a comparison of some stellar atmosphere models.

Although it has the disadvantage of being a very time consuming method when it is used following a standard procedure it is likely to have good results (*S. G. Sousa 2009*). The same author suggests in his work, that if we use equivalent width ratio, we can get good results in the measurement of this parameter. The equivalent width method has more information than the line depth method and shows significant consistency between the various calibrations. The work of the referenced author was inspired by the following statement: "There is no doubt that spectral lines change their strength with temperature, and the use of the ratio of the central depths of two spectral lines near each other in wavelength has proved to be a near optimum thermometer" (*Gray 2004*). Therefore, the relationship between the equivalent widths of two lines with different sensitivities temperature is an excellent method for measuring the star's effective temperature.

Although this method can still be questioned it has been proved that it achieves results with good precision in the most favorable cases.

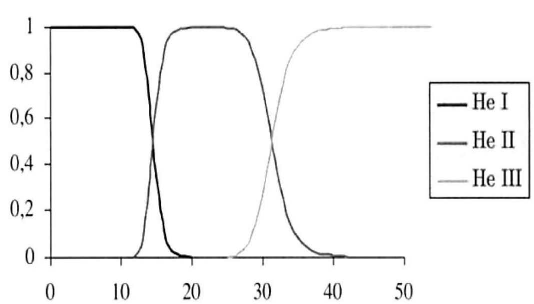

Figure 5: The equivalent width method uses the ratio between ionized elements that can be related to the temperature, this graph shows us the relation between the ionized Helium ratio and the star's effective temperature (in thousand Kelvin)

As the graph shows, the star's effective temperature depends on the ratio between He I, He II and He III, we can conclude that at 15.000 Kelvin in a star with Helium, the ratio between He and He I is 0.5 and the ratio between He and He II is also 0.5, at 37.000 Kelvin, all the Helium is ionized into He III.

Using Saha ionization equation, we have:

$$\frac{n_{i+1} n_e}{n_i} = \frac{2g^0_{i+1}}{g^0_i} \left(\frac{\sqrt{2\pi m_e kT}}{h}\right)^3 \exp\left(-\frac{I_i}{kT}\right) \qquad (10)$$

where the index i indicates the state of ionization and $I_i = E_{i+1} - E_i$ is the ith ionization energy of the atomic species. The Saha equation is usually solved replacing the variable n_e by p_e using the ideal gas law:

$$\frac{p_e}{kT} = n_e \qquad (11)$$

we have:

$$\frac{n_{II}}{n_I} = \frac{g_{II}\, 2 (2\pi m_e)^{3/2} (kT)^{5/2}}{g_I\, p_e h^3} \exp\left(-\frac{I_I}{kT}\right) \qquad (12)$$

Given that:

n_I — Helium density in the first state of ionization (He I)

n_{II} — Helium density in the second state of ionization (He II)

g_I — Helium degeneracy at the first state of ionization (He I)

g_{II} — Helium degeneracy at the second state of ionization (He II) m_e — electron mass — 9.10938356E−31

k — Boltzmann constant — 1.38064852E−23 m^2 kg s-2 K-1

h — Plank's Constant — 6.62607004E−34 m-2 kg s-1

I_I Helium ionization energy — 3.93933574 E−18 J

p_e – Partial pressure produced by the electrons in the stellar atmosphere

T — Star's effective temperature in thousands of Kelvin For He I and He II, we have:

$$\frac{n_{II}}{n_I} = \frac{4204990 \cdot T^{\frac{5}{2}}}{p_e} \exp\left(-\frac{285.58}{T}\right) \quad (13)$$

From here we can deduce the star's effective temperature, knowing the amount of ionized Helium (He I and He II). Helium is the best element for our study because it is a regular element in WR stars.

As we know, a star's partial pressure p_e varies slightly, from about 1 Pa in the atmosphere of cooler stars to tens of Pa. If we consider $p_e = 10$, we will have that, in the exact moment when the He I ratio is the same as the He II ratio, the star's temperature is 14.500 Kelvin.

The Saha ionization equation allows us to evaluate the temperature range for which we can observe spectral lines of ionized elements. For example, from the graph, we can easily conclude that He II can be observed in stars with effective temperatures between 12.000 and 35.000 K.

Such calculations can be made to determine star's temperatures using its spectrum. We used He, but other elements can be used by varying the degeneracy factors and the elements ionization energy.

The problem with WR stars is the pressure factor p_e. Although not yet fully established, WR may not have any convective envelope so, pressure values can not be calculated. This is the problem concerning this method for WR star's effective temperature determination.

6.4. Density

The width of the lines present in the absorption spectra of stars allows us to calculate another physical quantity: the gas density at the surface of the star, that is, the amount of matter per unit of volume. From there, it is possible to estimate the star brightness and, in turn, deduce its mass. The wider absorption lines are, the greater is the gas density in the star atmosphere. Meanwhile, it is known that stars with denser atmosphere are least bright and also have lower mass.

6.5. Velocity

Another physical quantity that can be determined by spectroscopic studies is the different speed at which stars move relative to the observer along the direction of observation, i.e. along the direction according to which we look at.

This quantity is called radial velocity and is of great importance in astronomy. The study of radial velocity of distance galaxies allowed us, in the 20th century, to conclude that the universe is expanding. That was one of the most remarkable discoveries in the history of science. Today it is known that the universe we know was originated about 13500 million years ago, thanks to radial velocity studies.

The phenomenon that allows us to determine the radial velocity is known as the Doppler effect. This effect is often perceived by us when we hear a car honking while he is approaching our position and, after, when he is moving away from us. During the approach, the sound seems to be more acute (higher frequency), becoming a more grave sound (lower frequency) when he moves away.

The Doppler effect happens with any wave phenomenon, and that also applies to electromagnetic radiation. In this case, the Doppler effect is only noticeable if the speeds involved are relatively high.

When the electromagnetic waves source (that, in this case, can be a star or a galaxy) approaches the observer, the radiation frequency seen by the observer increases relative to that emitted. This effect is known as blue shift. The reverse phenomenon occurs if the object moves away from the observer and is known as red shift.

But, how do you know if the light that reaches us from a star is diverted to blue or red? The answer to this question is obtained by comparing the observed spectrum of a star with the spectrum emitted in laboratory, at rest, by a known gas.

In picture 11, in the middle panel, you can see an emission spectrum obtained in laboratory. The top panel is a spectrum that belong to a star with zero radial velocity.

Figure 6: The emission spectrum (middle panel) is a synthetic benchmark, it is a reference spectrum. On the top spectrum we can see that absorption lines are located at the same position of the corresponding lines on the reference spectrum. The lower spectrum has its lines shifted, this means that, in this case, the object is moving away from the observer

We can see that the star's spectrum absorption lines are in the same position as the emission lines obtained in laboratory. The lower panel represents a spectrum that belongs to a star that is moving away from the observer. The absorption lines are shifted to the right in relation to the reference spectrum, in this case, we have a red shift, i.e. star radiation has lower frequencies.

By measuring the shift seen in the spectrum, we can determine with good accuracy the star's radial velocity.

Mathematically, radial velocity v, also called recession velocity, can be calculated by the expression:

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c} \quad (14)$$

$$|v| = \left| c\frac{\lambda}{\lambda_0} \right| \quad (15)$$

where λ is the referential wavelength, λ_0 is the observed wavelength and c is the speed of light in vacuum.

For example, if we obtain a spectrum where $H\alpha$ has a wavelength of 662 nm and knowing that the reference $H\alpha$ line has a wavelength of 656 nm, we can calculate the star radial velocity, by using equation 11 :

$$|v| = \left| 3 \cdot 10^8 \cdot \frac{656 - 662}{662} \right| \quad (16)$$

$$v = 2{,}74 \cdot 10^6 ms^{-1} \quad (17)$$

6.6. Gravitational Acceleration

The effective gravity on the surface of the star g_e is given by the equation:

$$g_e = (1-\beta)\frac{GM}{R^2} \quad (18)$$

where M is the star mass, G is Newton's gravitational constant and β is the ratio between radiation pressure P and the star's gravitational force g, expressed by:

$$\beta = \frac{P}{g} \quad (19)$$

This ratio is used as a correction to the gravitational force at the star's surface due to the force exerted by the radiation pressure, opposing the gravitational force. That is, we need to consider a counter force that is subtracted to the gravitation force.

By analyzing the ratio equation, we can think about three possible cases:

- If $g > P$, the ratio will have a value in the range between 0 and 1 and the gravitational force will be reduced
  (If $g < P$, $\beta \in]0, 1[$)
- If $g = P$, the ratio will be 1 and gravitational force is canceled by radiation pressure
  (If $g = P$, $\beta = 1$)
- If $g < P$, the ratio is greater than 1, radiation pressure will be bigger than the gravitational force
  (If $g < P$, $\beta \in]1, +\infty[$)

Since we are working with the most luminous and massive stars known to date, the radiation pressure phenomenon needs to be significantly considered. It is explained as the pressure exerted in a surface due to the incidence of electromagnetic radiation.

It should be noted that, although mathematically possible, there is no knowledge where the second or third case represents a physical possibility.

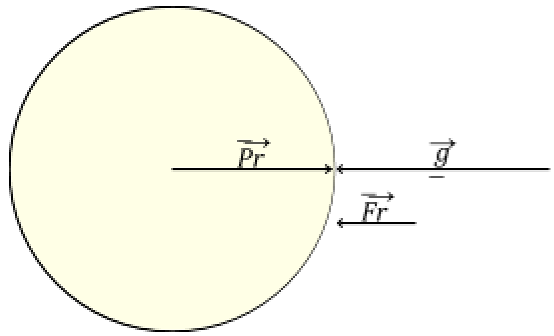

Figure 7: This diagram explains the phenomenon of star surface gravitational force *Fr* decrease due to the radiation pressure *P*,opposed to the gravitational force *g*

7. Equivalent Width Method

The equivalent width of a spectral line is a measure of the area of the line on a plot of intensity and wavelength for a certain spectral line.

It is used as a quantitative measure of the spectral line strength and the element's density. The spectroscopy software we used can do this calculation for us, given a certain element line, it will give us it's equivalent width value.

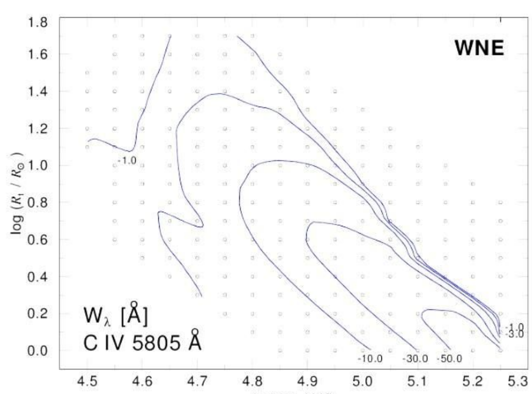

Figure 8: Contours of equivalent widths of the C IV line at 5805 Å

We used the equivalent width method to determine the star's radius and temperature. By using two aligned contours of equivalent widths labeled in different wavelengths, we can superimpose their equivalent width contours and get the intersection, where the star's radius and temperature will be.

For example, a star with the equivalent −1 and −1 for the lines C IV 5805 Å and He I 5876 Å, respectively, will have a radius of $10^{1.5}$ = 25 times the solar radius and a temperature of $10^{4.5}$ = 31622 Kelvin.

Figure 9: Superimpose of contours of equivalent widths of the C IV line at 5805 Åand He I line at 5876 Å

8. Wolf-Rayet Stars

Wolf-Rayet stars are a class of peculiar stars, first identified in *1867* by *C.J.E. Wolf and G. Rayet*. Unlike most stars spectra, that are dominate by narrow absorption lines, WR stars spectra show clear emission lines. WR spectra, with prominent emission lines, make them easy to identify, which, in our case, is an asset.

The base model for WR stars is a massive, hot star that is suffering from extreme mass loss. The mass loss occurs due to the its continuous stellar wind that happens at the star's surface and can accelerate from low velocities to velocities that exceed the star's surface escape velocity.

This mass loss usually exceeds the value of 10^{-5} solar masses (*M*) per year and is enough to affect the star's evolution. Usually, this wind's velocity varies between $800km^{-1}$ and $3000kms^{-1}$ this exceeds the star terminal velocity ($v\infty$).

Generally, it is believed that, although it has not been rigorously proved, the mass loss occurs due to the radiation pressure which acts on various transitions on the iron atom and others atomic species in the UV extreme ($\lambda < 900$). In addiction, it is believed that the star wind's composing material's temperature is lower than the effective star temperature. The energy that makes up the wind comes from photoionization by the intense UV radiation field produced by the star.

The WR stars that belong to the population I, that is, young and hot stars that are, normally, found in the spiral arms of the galaxy, have a distribution similar to stars of spectral class O. This kind of stars are typically located in the arms of our spiral galaxy or near the *H II* galaxy regions. It is also important to note that many massive stars, including the class O stars, pass by a WR phase at the end of their lifetime before exploding.

As for its features, WR stars have masses ranging from 5 to 60 solar masses and their temperatures vary between 25.000*K* and 100.000*K*. Due to the spacial association between class O stars and WR, it is believed that WR are descendants of class O stars. Currently, only about 220 WR stars are known in our galaxy, but this number is certainly incomplete.

Most WR are hidden by space dust, which absorbs and scatters light within our galaxy(a phenomenon called stellar extinction). Some estimates indicate that the total number of WR stars in our galaxy range from 1.000 to 2.000 stars.

WR rarity are due to their initial mass, that favors the production of a low mass star, and the short duration of the phase life of a WR star, which are estimated to be of 10^5 years. All the stars more massive than 25 solar masses go through a similar phase as the WR phase.

9. WR Evolution

WR stars are also an advanced stage of high mass stars, usually O-type stars, that have very intense stellar winds and very high radial velocities.

Originally, it was thought that these stars existed only in binary systems: initially, the most massive star would fill Roche lobe and would, consequently, lose mass and its outer envelope, rich in hydrogen, eventually, the inner layer, rich in heavier elements, would explode. That is, the star's convective envelope would be released, exposing the inner layers of the star.

However, *Conti (1976)*, proposed the theory most widely accepted for most cases: the WR stars could be a natural stage in the evolution of high-mass stars (O-type). That is, it is believed that the WR stars are descendants of O-type stars. The base sequence for the evolution of WR stars is:

$$O \rightarrow Of \rightarrow WR$$

Since then, the theoretical work and observation led to a refining of this sequence. For WR stars with more initial mass than 50 solar masses ($M_\odot$), sequence is:

$$O \rightarrow Olf \rightarrow BSG \rightarrow LBV \rightarrow WN \rightarrow WC \rightarrow Supernova$$

while stars with masses between 35 and $50\ M_\odot$ have the following alternative sequence:

$$O \rightarrow BSG \rightarrow YSG \rightarrow RSG \rightarrow YSG \rightarrow WN \rightarrow WC \rightarrow Supernova$$

Other sequences have also been proposed, but the path that this type of stars go through (which depends on the initial mass and composition, its rotation rate and whether or not has a partner) is still uncertain.

10. WR subtypes

WR stars are divided into three major spectroscopic groups, WN, WC and WO, based on the lines present in their emission spectrum.

WN stars have emission lines predominantly of helium and nitrogen, while carbon, silicon and hydrogen emission lines can also be observed in some of the spectra of this class of stars.

In contrast, WC spectra have predominantly, carbon and helium emission lines. Being absent, in these objects, hydrogen and nitrogen emissions.

WO stars are the rarest WR observable, their spectra are similar to WC stars spectra, except that the oxygen lines reveal greater intensity in this class than the two previous types. In these stars, it is also usual to observe lines resulting from high energy ionizing elements.

These spectral classes may be further divided into subclasses based on the particular types of lines, yielding up and ionization rating.

WN stars that exhibit an emission spectrum with elements with high ionization energy (e.g. He II, N V,O VI) are designated as WN2. By contrast, those who show an emission spectrum with low ionization energy elements (eg. He I, N III) are classified as WN9, although recently, the spectra classification WR was expanded to WN11.

Likewise, in WC stars, we can also find emission of elements with high ionization energy emission (e.g. He II, C IV, O VI), this stars are designated by WC4, while those that exhibit elements with a lower ionization energy (e.g. He I, C II) are called WC9.

It is also usual to denominate WN stars with classes from 2 to 5, as of "early" (WNE) and with classes from 2 to 9 as "late" (WNL). Likewise, WC 4-6 stars are designates as WCE while WC 7-9 stars are designated as WCL. Although there are notable exceptions, WNE stars generally show no evidence of hydrogen emission while it can be found in WNL stars.

11. WR study importance

The rarity of WR stars does not mean they are not important. Contrariwise, over the life of a galaxy, WR stars have a big energetic, dynamic and chemical influence, they are important in the evolution of the interstellar environment. Thus, WR stars are correlated in various ways with some important galactic phenomena existing in the universe.

12. AGN Phenomenon in Galaxies

The phenomenon referred to as "AGN – Active Galactic Nuclei" is still very poorly understood. It is the formation , at an exceptionally high rate, of stars in a galaxy. Especially in areas near the galaxy core where there is more gas and dust.

WR stars provide a unique opportunity to study this phenomenon using spectroscopy. There are cases of far away galaxies where WR stars are visible so that we can extract their spectrum, however, this cases are outside our study projections.

13. Emission nebulae

WR stars are ofter related to emission nebulae. Many WR known are central stars in some of these nebulae. They also contribute largely in the Nebula gas volume since, during their activity, WR stars emit ionized gas that interacts with the surrounding nebula gas.

For example, in the WR 136, one of the stars largely studied in our project, the mass ejected as ionized gas by the star due to its stellar wind feeds the volume of the growing Nebula (NGC 6888), where it operates as a central star.

14. Binary Systems

Approximately 50% of WR stars occur in binary systems. A value that can be compared with type O stars. It has been recognized that WR stars could only be originated in binary systems.

The mass loss of an early WR star causes the moved mass to establish and maintain a second star due to the matter outflow from the Roche lobe. The great uncertainty in evolutionary computation of this kind os system is the amount of material lost during Roche lobe overflow, i.e. the matter that is not aggregated by the companion star.

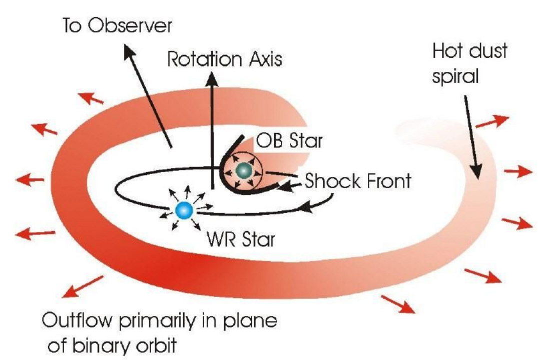

Figure 10: Scheme representing the star binary model with the WR 104 star

We can consider three main types of binary systems of WR stars, WR L OB, WR L WR and WR L compact stars (black holes or neutron stars).

Binary systems are extremely useful because they allow us to make a direct determination of both stars mass, regardless of the evolutionary model. Using these mass values in a one star system assumes that WR stars from binary systems have similar properties as lonely WR stars. This cannot be tested due to uncertainties associated to WR stars properties and poor amount of statistics related to this kind of stars.

15. Methodology and Setup characterization

We performed 8 observation sessions with two different setups.
In the first session we used a movable setup, in the remaining sessions we used a fixed setup.
We used the movable setup so we would be aware of the manual process. All the processes were repeated several times, until we had a perfect mastery of the methodologies and processes involved.

Set specifications:

16. Digital imaging systems

In a digital system of image, the matrix is extremely sensitive to light , which allows a low exposure, the final image can be obtained quickly through intermediate steps that do not make the process slow and the image is measured which enables the wide variety of image processing and storage of information for an unlimited time.
Basically, a digital image sensor is composed of:

- CCD or CMOS matrix: a photosensitive cell assembly formed by rows and columns;
- Peltier: a device for cooling the CCD array to the operating temperature;
- Circuit board: electronic circuit that controls the camera functions;
- Shutter: Controls the light input;
- Cable entry: connects the camera to the computer;
- Optical windows: generally, made of quartz
- Filter Adapter;
- Cove Box;
- Mounting Bracket.

17. CCD

A *Couple Charged Device* (CCD) is formed by a set of sensors, called *photoelectric cells* or *pixels* arranged in a matrix of rows and columns.
These sensors are more sensitive to light that silver crystals of conventional films. The physical principle used to obtain digital images is based in the fact that some materials have the property, when illuminated, to absorb photons and produce electrons. This is known as the photoelectric effect.
The light that hits the CCD array sensitizes it's photoelectric cells and creates free electrons in an amount proportional to the light received. This process can be thought of as the capture of rainwater with many buckets, where each photon is a rainwater drop an each bucket is one of the array sensors. After some time, we will have some buckets with more water, as these are receiving more water, and buckets with less water, receiving less water.
In the image then appears on the screen, the information is arranged similarly to the matrix, the position of a given sensor and the light intensity received by it will be associated to a color or a tone. For the computer, the image is nothing more than a set of numbers that can be manipulated in order to increase the image contrast, making it brighter or darker, or highlighting details that are invisible to our eyes.

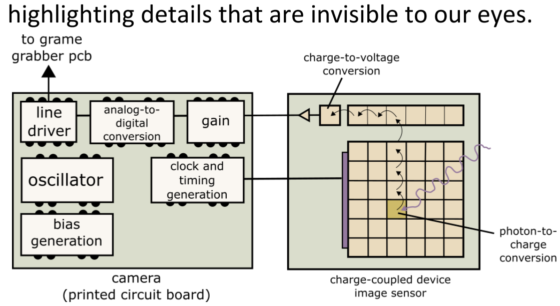

Figure 11: Scheme of a CCD camera. The basic principle in the construction of an image is the conversion of energy from a photon to an electrical charge and from the electrical charge to a potential difference that is converted into ADU (Analog-digital unit) units

18. Getting Images from a CCD

As mentioned above, the image is converted into numbers that indicate the position of each sensor and the light intensity received by it. However, the numbers are easily manipulable, and this allows us to enter the digital imaging field.

In conventional photographic film, when the film is under or over exposed to light, we can do hours and hours of exposure and not get a good result of the shot. We can then use chemical resources to improve the outcome. However, these features are complicated and sometimes expensive and irreversible. A small mistake can damage the device.

The scanning, or the conversion of analog information into digital refers to load the translation process from the sensor to a binary format that is recognized by the computer. A camera with 12-bit equivalent to 4096 gray levels, while a camera with 16-bit has an output of 65,536 gray levels, there is a big difference between them.

Astronomers that use digital detection systems run less risks because the computer becomes the photography treatment darkroom and this treatment can be done quickly, in a matter of seconds.

19. Image calibration and processing

A calibrated image is not, usually, the final image. The data reduction is only completed when all efforts have been made to optimize the image's quality. For that, we use several software tools, although there are a several problems with software automations that produce final images for astronomy study. The work involved in the data reduction to produce the final image can be resumed to brightness and contrast controls of the image.

The first analysis to run is the pixel's value histogram. For example, on the 16-bit System, these values are between 0 and 65535 ADU (analog-to-digital units) but there will be some pixels that are either "dead" (with 0 ADU) or "saturated" (with maximum ADU). The information about the CCD linearity should be known so that pixels that have counts above a certain pre-arranged value (e.g. 40,000 ADU) can be erased or ignored.

An important characteristic is the image "gama". Gama is defined for "thrust-worthy pixels", the ones that are going to be used to produce our final image. Usually these would be all that are not completely "white" of "black", if the BIAS and the pixel non-linearity didn't complicate the process. So, if we designate as "white" all pixels above the limit of pixel non-linearity and "black" all the pixels all pixels that have less ADU counts than the medium black sky counts, we come up with the expression:

Gama = "white"(min) – "black"(máx)

This way, histogram analysis allows us to establish which gama value is in the best interest of the final image production, in a way that the image's contrast may be optimized.

Because stars have an elevated apparent brightness, they do not have any problems with wide gama values. However, for galaxies or nebula to be seen in the final image, is important to make a gama value restriction, since galaxies and nebulas are less bright than stars.

20. FITS

FITS, or Flexible Image Transport System is a digital file format used to store, transmit, and manipulate scientific images. *FITS* is the digital format most used in astronomy. Unlike many image formats, *FITS* format is designed specifically for scientific data and therefore includes a lot of information about the photometric and spacial calibration parameters along with the raw data from the image source.

An important feature in *FITS* format is that the image raw data is stored in a human readable ASCII header so that a user can review all information contained in the capture, including the author, the date, the instruments used and even the image coordinates (among other information).

FITS files are also used to store non-image data, such as spectra, data cubes, or even structured data. A *FITS* file may further contain various extensions, and each of these can contain a data object. For example, you can store X-rays data and infrared exposures in the same file.

Astronomers working with Hubble Space Telescope often get spectacular images based on raw data taken by the orbiting instruments. But, thanks to a recent software, this power is reachable to a non-scientist or anyone equipped with a computer and a image editing software.

The software, called *FITS Liberator*, is actually a plugin for *Adobe Photoshop* and is available in the European Hubble website. This plugin allows satellite pictures enthusiasts to work these data that were once only reserved for astronomers with highly specialized tools.

The *FITS Liberator* allows computer users to manipulate astronomical images in the *FITS* format, allowing *Photoshop* and related softwares to accept the images as if they were *JPEG* or *GIF* files.

Scientist from the European Space Observatory, European Space Agency and NASA were who developed this software. *FITS* images, are available in many public archives, such as those who are still kept in the Scientific Institute os Space Telescope, that operates Hubble for NASA. Other images as *JPEG* and *GIF* format also contain image information, but not as flexible.

21. Diffraction Grating

The diffraction grating is a device with multiple slots that diffract incident light rays. The use of diffraction gratings is important in astronomy, its ability to split light into its various wavelengths creates a spectrum that can be studied to determine various characteristics about stars or bodies that emit or reflect light.

The diffraction gratings are characterized by theei density of lines, i.e. equally spaced parallel grooves that exist per millimeter. The higher this number is, the higher the spectra resolution.

The most important concerning formula for diffraction gratings is given by:

$$\sin\alpha + \sin\beta = 10^{-6} kn\lambda \qquad (20)$$

where:

α — incidence angle β — diffraction angle k — diffraction order n — lines density (in lines per mm) D_v — deviation angle λ — wavelength in vacuum

If this given equation is applied for systems where $\mu_0 = 1$, $\lambda_0 = \lambda$

In most monochromators, the location of the input and output lines is fixed and the grating rotates around a plane through the center of his face. Therefore, the deviation angle D_v is a constant given by:

$$D_v = \alpha - \beta \qquad (21)$$

If we want to determine a certain wavelength for α and β values, the grating equation can be expressed as:

$$10^{-6} kn\lambda = 2\sin\left[\frac{\beta+\alpha}{2}\right]\cos\left[\frac{\beta-\alpha}{2}\right] \qquad (22)$$

Assuming that the D_v value is known, α and β can be determined by equations 21 and

22.

Using equation 20, knowing the grating's lines density, α and β we have that:

$$k\lambda = \text{constant} \qquad (23)$$

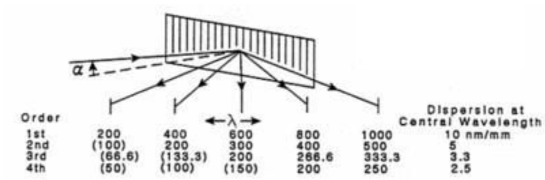

Figure 12: Scheme of the different diffraction orders produced by a diffraction grating

22. Observation Sessions

During the project, there were several observational sessions to collect the data necessary for the spectroscopic analysis of the WR stars.

The observations were made with a 5" refractory telescope, a *Celestron CG5* mount and a *ATIK 4000* CCD camera.

In addition to these, we carried out observations for the more difficult targets in the *Astronomical Observatory of Gualtar*, in Braga, with the partnership and guidance of *ORION – Sociedade Científica de Astronomia do Minho* and, along these observations our method and protocol for image collection gradually evolved.

We carried out 16 sessions for data collection, of these, only 11 were well succeed. The rest were conditioned by weather conditions or problems with the setup used.

The targets were mainly WR stars – WR1, WR4, WR5 and WR7 – and Alphecca star, used as a wavelength calibration spectrum.

Although it was difficult to find the targeted star in some cases, the spectrum characteristic of a WR , with prominent emission streaks, often allowed a direct identification of the target.

We also noticed two important things, when the brightness of the star is very low (magnitudes that range from 9 to 12), the spectrum signal is weak and the resulting graph shows very subtle emission streaks. So, we proceeded to the stack method to get a spectrum with a stronger signal. In addition, we also learned that the ideal focus used for the star was not the same as the ideal focus for the spectrum. So, we tried to focus the spectrum, and not the star, whereby, there was an improvement in the results.

On these observations, we also added more targets, such as the WR136 and WR140 stars. The goal was to use the method that we had been perfecting to extract more and better images. It was in these further observations that we got the best spectra, with better detail and clarity.

23. Data Reduction and Processing

Our image were captured in various image formats. However, because the spectra processing software that we use, *VSPEC*, only recognizes *BMP* and *FITS* files extension, we always did the conversion to these formats.

In the first tests, we used *DMK41* and *ATIK4000* CCD cameras. The *DMK41* camera captures *AVI* movies or *BMP* images, while *ATIK4000* captures *FITS* with exhibitions ranging from 0.001 s and 60 min. Test stars, were, initially, bright stars. In these cases, the majority of exposures per frame never exceeded from 2 to 10 seconds.

The spectra data reduction always starts with the reduction of the CCD images: dark maps, bias, flat, but with extra care in the normalization of the flatfield, since the sky enlightenment is not homogeneous with respect to the various wavelengths.

The images were all first treated in *MAXIM DL5* were the data reduction was implemented. After this stage, the final image is always saved in *FITS* format (black and white) with 16-bit, ready to be treated in *VSPEC*.

The purpose of this task is to get a horizontal image, allowing us to make an easier data binning. The next step is to select the spectrum area where we want to extract the spectrum profile and use the command "Object Binning" to execute the raw spectrum data.

24. Spectrum Calibration

When we obtain the raw spectrum (calibrated only in pixels) we have to calibrate the spectrum in terms of wavelength.

We can calibrate the spectrum in three ways, with a properly calibrated reference spectrum (Alpheca for example), using the line of a green or red laser (well known wavelengths) or recognizing some predominant lines in the spectrum (H-α and H-β are the most common). However, it is necessary to keep the same setup to use this calibration methods.

To get the spectrum wavelengths in Angstroms, first we have to overlay the two spectra. By using the "Copy" command and then the "Paste" command we can overlap both profiles. The two spectra must, necessarily, have the same dispersion, i.e. they must be captured under the same conditions.

After the spectra are overlapped, we should go to the "Edit" menu and then use the "Replace" command to replace the star's profile as "Reference 1".

The next step is to match both stars zero order. For this we use the "Operations" menu and the command "Translate" causing causing the stars to get coincident.

Now we are able to make the reference spectrum calibration which will result in the calibration of the desired spectrum - Alpheca spectrum.

We need to go to the "Tools" menu and in "Elements" we select the hydrogen reference lines.The we go to the "Calibration" menu, choose "Calibration multiple lines" and indicate the number of visible lines. This calibration is called "Non-linear".After this, we hold the left mouse button while we select the area referring to the the line peak of the region and in the "Elements" meny we select the corresponding wavelength.

The spectrum will thus be calibrated in Angstroms and we can check the correctness of the calibration using the menu "Elements". Clicking on each of the wavelengths it is possible to check the element corresponding to each line profile .

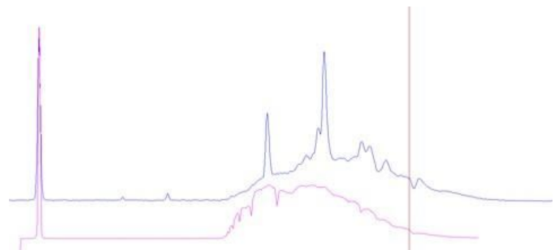

Figure 13: Spectra calibration using the Alphecca star

The spectrum is from now calibrated for both stars. Now we turn off the "Reference 1" and use again only WR 140 in which we apply the "Crop" tool so that the final result is the only thing that interests in the spectral profile.

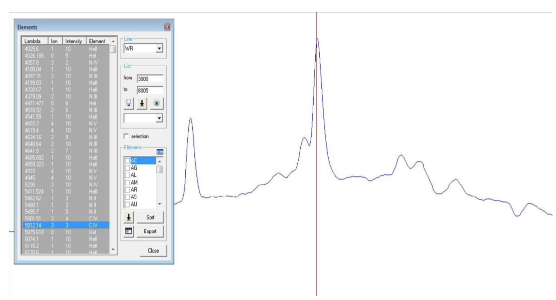

Figure 14: Final appearance of the calibrated spectrum with the elements menu

25. Standardization and Instrumental Response

To obtain perfectly calibrated spectra it is required to perform two operations, the standardization and correction of instrumental response. The flow is normalized, dividing the profile with a median of continuum (no spectral lines). The instrumental response is intended to correct the CCD sensitivity differences at different wavelengths. It is also the process of making our spectrum comparable with spectra of the same object, performed in different equipment.

To perform this correction our star's spectrum will have to be divided by the calibrated spectrum of the same star. This is done using spectra from a database with calibrated spectra that can be found online or in *VSPEC* library on the "Tools" menu under "Library".

So we just have to be careful to choose the right profile and then insert it on the spectrum of our star. As this is a calibrated spectrum it will correct differences between our system and a properly adjusted system. The spectrum is now ready for the final calibration phase. We opened the instrumental response and the calibrated spectrum and go to the "Operations" menu and select "Divide the profile by the profile" while we have the calibrated Alphecca spectrum selected. The end result is the "profile" of the star calibrated as a function of tools used and can be compared to other spectra obtained by other observers or instruments.

26. Final Results

26.1. Chemical Analysis

After we treat and calibrate our spectra, we proceed to the identification of chemical elements for each emission peak. As stated above, we used the analysis software "Vspec" and its elements library for assessment. The results can be found in this article's Attachments.

26.2. Radial Velocity

Using the concept of the Doppler effect (equation 15) and using the radial velocity equation previously stated, we analyzed, for each star, two prominent emission peaks and compared this values with the elements laboratory wavelength value. The reason we use two different peaks is based on previous scientific papers reporting differences between the radial velocities values for different peaks.

Thus, we made three calibrations and three measurements for each line, performing then the statical mean of the results.

The final velocity v is the statistical mean between the average values of each line , λ refers to the wavelength and v to the radial velocity.

WR136:

He II line:

laboratory λ : 6560.10 Å
observed$_1$ λ : 6579.79 Å
observed$_2$ λ : 6590.68 Å
observed$_3$ λ : 6588.40 Å

$$v(1) = 898 \text{km/s} \quad (1\text{-}1)$$

$$v(2) = 1392 \text{km/s} \quad (1\text{-}2)$$

$$v(3) = 1289 \text{km/s} \quad (1\text{-}3)$$

(1-4)

$$v_{mean} = 1193 \text{km/s}$$ **He II**

line:

laboratory λ : 5411.13 Å
observed$_1$ λ : 5424.13 Å
observed$_2$ λ : 5435.01 Å
observed$_3$ λ : 5425.63 Å

$$v(1) = 1697 \text{km/s} \quad (2\text{-}1)$$

$$v(2) = 1296 \text{ km/s} \quad (2\text{-}2)$$

$$v(3) = 780 \text{ km/s} \quad (2\text{-}3)$$

$$v_{mean} = 924 \text{ km/s} \quad (2\text{-}4)$$

$$v_{final} = 1059 \text{ km/s} \quad (2\text{-}5)$$

WR140:

C IV line:

$v(1) = 1970$km/s (3-1)

$v(2) = 1316$km/s (3-2)

$v(3) = 1376$km/s (3-3)

$v_{mean} = 1554$km/s (3-4)

He II line:

laboratory λ : 6562.80 Å
observed$_1$ λ : 6590.16 Å
observed$_2$ λ : 6601.05 Å
observed$_3$ λ : 6601.05 Å

$v(1) = 1245$km/s (4-1)

$v(2) = 1738$ km/s (4-2)

$v(3) = 1738$ km/s (4-3)

$v_{mean} = 1574$ km/s (4-4)

$v_{final} = 1564$ km/s (4-5)

laboratory λ : 5801.31 Å

observed$_1$ λ : 5839.66 Å

observed$_2$ λ : 5827.08 Å

observed$_3$ λ : 5828.24 Å

WR4:

C IV line:

$v(1)$ = 742km/s (5-1)

$v(2)$ = 389km/s (5-2)

$v(3)$ = 742km/s (5-3)

v_{mean} = 627km/s (5-4)

laboratory λ : 5812.14 Å observed$_1$ λ : 5826.56 Å observed$_2$ λ : 5819.86 Å observed$_3$ λ : 5826.56 Å

Catalog Name	Spectral Type	R? $[R_\odot]$ (*Potsdam*)	R? $[R_\odot]$ (*ESO*)	T? [*kK*] (*Potsdam*)	T? [*kK*] (*Potsdam*
WR4	WC	[2 ; 7]	No data	[126 ; 12]	No data
WR136	WN	2	2.63	89	63.096
WR139	WN	Imp.	No data	Imp.	No data
WR140	WC	14	No data	53	No data

Table 1: Results of the spectra analy-sis

27. Conclusions and Discussion

The Wolf Rayet stars analyzed in this study have different metallicities, spectral types, temperatures and other characteristics that differentiate them from one another. Our study requires precisely the knowledge of the proprieties and characteristics of the stars in study. Between our projects initial goals, we have the study of high mass star populations for better understanding of AGN galaxies, emission nebulas and binary systems that involve WR stars. However, our main objective was to understand the chemical and astrophysical dynamics of WR stars. Also, the stellar parameters determined in this study allowed us to identify certain characteristics of the surrounding environment where WR stars are located. It's important to note that at the time of the data collection, many WR stars in catalog where badly placed in the night sky, meaning that they were close to the horizon, turning data extraction into a challenge. However, we collected spectral data from 7 WR stars, in which only 4 had good results of intensity and spectra resolution. Besides that, when we compared our spectral data with other astronomers, we concluded that our spectral profiles were very similar in terms of resolution and line quantity and detection. Jim Ferreira, one of the astronomers that we collaborated with, informed us that "This looks really good. You've captured all of the major lines. Well done!"

In this research, the WR 136 analysis allowed us to conclude that the Crescent Nebula (NGC 6888) is most likely fed by the He II rich ionized gas and that the nebula is, as it appears in catalogs, an H II region, given its chemical composition. However, we also detected the presence of other ionic elements, such as N III, C IV and N IV (Ionized carbon and nitrogen). When calculating radial velocities, the final value for radial velocity concerning WR 136 is around 1000 km/s. This means that the star, as expected from a WR star, is expelling matter at a blistering pace, contributing the nebula's increase in volume. Although some papers refer the possibility of WR

136 being a binary star, this calculated radial velocity only shows the conjugated velocity of the system, equivalent to the vector sum of orbital velocity and stellar wind velocity. After resorting to the equivalent width method, we determined two sets of temperature and star radius. According to models published by one of the European Southern Observatory (ESO) papers (*W. Schmutz, W.-R Hamann and U. Wessolowski – 1988*), WR 136 has a temperature of 63,000 kelvins and a radius 2.63 times bigger than the radius of the sun. But, according to models published by the Potsdam University, WR 136 has a temperature of 89,000 kelvins and a radius 2 times bigger than the sun's. As explained in the equivalent width method, this difference of values in temperature and radius is given by the different models used and their own characteristics.

The analysis to WR 140 reveals mainly carbon emission lines (C III and C IV), although also being detected He I and He II emission lines. This confirms that WR140 is WC type star, probably with high ionization energy involved, since carbon is ionized three times (three electrons are removed from each carbon atom). Also, stellar winds are then mainly composed by metals instead of gases and have really fast ejection speeds. When calculating its radial velocity, the final value is around 1500 km/s. Once again, WR 140 is also proved to be a binary system, but if the radial velocity is this high, then the stellar wind velocity must also be very high as well, since we only observe the system's conjugated radial velocity. We can then prove the star's short life span, consequence of the high mass loss rates demonstrated by very high stellar wind velocities. Also, when comparing our final results with other professional papers, our values only have a relative error of 5%.

Besides that, WR 139 shows the presence of mainly He II emission lines, with residual emissions of carbon and nitrogen (C IV and N IV). However, WR 139 is a particular case when studying WR stars. It has been proved that WR 139 is a binary star with a massive O type star companion with really strange behaviors and difficult certainty in spectral analysis. In a way, this case was a barrier in our study, since we couldn't extract information about temperature, radius and even radial velocity when reducing spectral data. We can still conclude that the surrounding area of the star is most likely an H II region, similar to WR 136, or all the star's external layers of its envelope were released when the star went into the current WR phase.

Finally, when analyzing WR 4, we detected a similar spectral profile to WR 140 – a star with emissions mainly composed of C III and C IV and some residual emissions of other elements such as He II and O V (ionized helium and oxygen), that led us to the conclusion that WR 4 spectral type fits into the WC model with probable areas filled with metal, as mentioned above. In terms of radial velocity, the final value is lower than usual: 630 km/s. We couldn't compare this value with other data, since we didn't find any more certain information. However, because previous values have been quite precise, we do not disregard the importance of this value. As in terms of temperature and radius, pinpointing an exact value was complicated. The best we could do was to determine an interval of possible values for temperature and radius. So, this star has a very high temperature (between 126,000 and 158,000 kelvins) and its radius is between 2 and 7 solar radii. This values are a little discrepant in relation to the usual values, but we believe they have some accuracy.

As we can see from this data, and because WR are high luminosity stars, they have really strong stellar winds, which radial expansion is most likely supported by radiation pressure. It's also because of this winds that we observe prominent emission lines (*Beals 1929, Chandrasekhar 1934 and Wilson 1934*). This way, stellar winds eventually sweep these stars atmosphere with velocities mostly above 1000 km/s.

In the end, we consider our results of excellent quality, at a level extraordinarily close to some professional astronomers more experienced than us and with better instrumentation. This research allowed us to perceive the essence of scientific investigation. Our learning in this field of study was immense and very rewarding, that will have a major impact in our future learning processes. What seemed impossible at first site became motivating, fun, and, above all, a challenge. We proved that high school students, with the will to do so, can "be astronomers" as well, modeling stars as complex and enigmatic as Wolf Rayet stars, mainly because of their physical and chemical proprieties. This study took us far beyond astronomy and astrophysics, it took us learning about chemistry, mathematics, telescope mechanics and even graphic computation.

28. Acknowledgments

Finally, we thank everyone that contributed in our project, from the teachers that motivated us and helped us to give structure to the project to the investigators that had the kindness of providing us data and enlightening us about some questions. Below, we list those that were the most helpful to our project. Thank you all!

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