Spectroscopic analysis of the binaries systems Epsilon Herculis and HIP107162

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Abstract
During the 2022 internship involving a group of high school students at the Monte Baldo Astronomical Observatory (hereafter referred to as OMB) in Ferrara di Monte Baldo, Verona, Italy, the two stellar systems of HIP107162 and Eps Her were observed, and high and low-resolution spectroscopic analysis was conducted. The construction of the radial velocity curve allowed for the determination of the binary systems' structure, while the low-resolution spectra enabled the identification of present elements and consequently their spectral classification.

1 Introduction

A binary is a system composed of two stars that orbit around a common center of mass, attracting each other according to the law of universal gravitation (Equation 1).

$$F = G\frac{m_1 \cdot m_2}{d^2} \tag{1}$$

Binary systems can be classified based on the way their components can be observed. When the angular separation allows for telescopic observation, they are called visual binaries. When

the angular distance is too small to be observed from the ground, but the stars have an orbital plane nearly parallel to the observer, eclipses can occur during which one of the components partially or totally obscures the other. In this case, we have an eclipsing binary or photometric binary, as the eclipses cause detectable changes in brightness through photometric studies. Finally, when the system does not exhibit eclipses, the orbital motion can still be observed through spectroscopic studies, which detect the Doppler shift of spectral lines of the components, especially when they are very close and have high radial velocities. The system may display both stellar spectra or only one spectrum of the two components, as one star may be much brighter than the other. For our work, we have chosen the systems of Epsilon Herculis and HIP107162, both being spectroscopic binaries. The data were collected at the highest resolution allowed by the OMB spectrograph ($R \sim 10,000$) to accurately measure the separation between absorption lines (Figures 1 and 8) and, consequently, the radial velocities of the two components. These velocities will vary depending on the geometric position of the stars relative to the spectrograph's slit, exhibiting maximum velocity when they are perpendicular to the line of sight and reaching zero when they are parallel to it. A series of measurements at different positions allows for the construction of the radial velocity curve and, from these, the orbit of the system.

2 Observation

High-resolution spectra were acquired using the OMB's 0.25m F/10 Schmidt Cassegrain telescope and the SHELYAK LHIRES III+CCD Atik-460ex spectrograph equipped with a 2400 lines per millimeter grating, providing a resolution of 0.1527 Å/pixel and an average RMS of 0.005 in the spectral range of 4730-4930 Å. The reduction of high-resolution data was performed using the ISIS software developed by the French astronomer Christian Buil. Regarding the low-resolution spectra, another 0.25m F/10 Schmidt Cassegrain telescope at OMB was used, along with the ALPY600+CMOS ASI284pro spectrograph with a resolution of 4.96 Å/pixel in the range of 3800-8000 Å. Additionally, a 0.5m f/14 Ritchey-Chrétien telescope located at the Stroncone Observatory (MPC589) was used in combination with the MARK II+CCD Atik-460ex spectrograph, equipped with a 600 lines per millimeter grating in the range of 3800-7000 Å. Finally, the SHELYAK LHIRES III+CCD Atik-460ex spectrograph with a 600 lines per millimeter grating in the range of 3600-4600 Å was also employed at OMB.
The low-resolution data were reduced using IRAF version 2.16 software. All data were corrected for dark current, bias, flat-field, wavelength calibration using an ArNe lamp, sky background subtraction, heliocentric velocity correction, and flux calibration (only for low-resolution data). All data are available in the Monte Baldo Astronomical Observatory database under the research/spectroscopy/database section (Castellani et al.).

Observatory	Telescope	Spectrograph	Resolution-Grating
OMB	Schmidt Cassegrain 0.25m f/10	SHELYAK LHIRES III	HIGHT - 2400 ll/mm
OMB	Schmidt Cassegrain 0.25m f/5	Alpy600	LOW
OMB	Schmidt Cassegrain 0.25m f/10	SHELYAK LHIRES III	MEDIUM - 600 ll/mm
MPC589	Ritchey-Chrétien 0.5m f/14	MARK II	MEDIUM - 600 l/mm

Table 1 *:Instrumentation used for data collection*

star name	α	δ	mag(V)	revolution period [days]
Eps Her	17 : 00 : 17	+ 30 : 55 : 35	3.90	4.0235
HIP107162	21 : 42 : 23	+ 41 : 04 : 37	5.73	1.729

Table 2: *Binary systems observed by Monte Baldo Astronomical Observatory A. Gelodi*

3 Data Collection and Result

For each measurement of Epsilon Herculis, six exposures of 600 seconds each were obtained, while for HIP107162, the runs consisted of 5 exposures, each lasting 900 seconds. The spectrograph is a heavy instrument, and during target tracking, the hourly motion of the telescope causes slight flexures in the telescope/spectrograph connection, which can shift the position of the spectrum on the CCD. The processing program can recenter the images during summation, but to avoid the risk of calibration errors, we decided to capture the Ar-Ne lamp both before and after targeting. H_β at zero lambda (λ_0), corresponding to 4861.363 Å, was then chosen to calculate the radial velocity of the two stars by observing the shift of the two peaks in the processed spectrum. The formula used for this calculation is as follows:

$$Vr = \left[\frac{\lambda - \lambda_0}{\lambda_0}\right] \cdot c \tag{2}$$

3.1 Eps Her

Epsilon Herculis is a spectroscopic binary system located in the Hercules constellation, situated 155 light-years away from the Sun, with a visible magnitude of 3.9. There is disagreement in the literature regarding the stars that compose this system. Petrie (1939) classified the system as two components of spectral classes A0 and A2, Pourbaix et al. (1989) classified it as a spectroscopic binary system with a period of 4 days and an eccentricity of 0.02, while Cowley et al. (1969) classified it as type A0V. In 1995, it was classified as a Lambda Bootis star, but even this classification has been subject to debate.

3.1.1 High-Resolution Spectroscopy

Table 3 presents the data obtained from the spectra, including the Julian day (JD), phase of the primary star (phase), radial velocities of the two stars with respect to the phase (Vr_1 and Vr_2), and the error for each velocity (σ_{Vr_1} and σ_{Vr_2}).
Figure 1 shows three spectra of the Epsilon Herculis binary system at different phases, highlighting the orbital

JD	phase	$< Vr_1 >$	σ_{Vr_1}	$< Vr_2 >$	σ_{Vr_2}
2459704,474	0,000	33,9	2,8	-110,6	4,9
2459712,394	0,968	18,1	2,5	-104,6	10,0
2459714,403	0,468	-77,9	9,9	69,7	4,6
2459717,434	0,221	24,5	4,3	-52,2	2,5
2459758,426	0,409	-62,1	9,8	39,5	7,2
2459761,405	0,150	16,3	8,2	-101,3	9,3
2459767,399	0,639	-68,0	9,9	44,0	3,9
2459768,412	0,891	13,2	9,6	-75,8	8,2
2459769,432	0,145	16,3	8,2	-98,4	7,5
2459771,424	0,640	-67,8	4,6	42,2	15,3
2459773,394	0,129	23,7	9,6	-109,5	6,9
2459774,394	0,378	-58,7	4,9	21,2	0,4
2459776,481	0,897	8,7	3,0	-86,7	12,1
2459777,411	0,128	29,4	4,9	-102,8	9,6
2459779,387	0,619	-65,6	5,4	58,4	0,6
2459781,49	0,141	28,80	4,9	-96,80	12,1

Table 3 *:Calculated values of radial velocity for the binary system Epsilon Herculis*

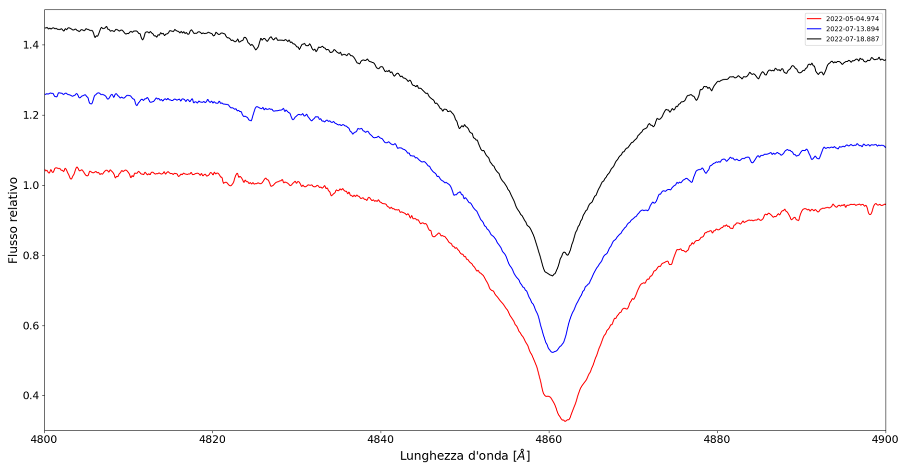

Figure 1 *: Some spectra of the Epsilon Herculis system taken from the database of the Monte Baldo Astronomical Observatory*

motion of the system. The presence of one or two peaks is determined by the positions of the two stars at the time the spectrum is obtained, with a single peak indicating that both stars are in line with the observer (thus Vr close to zero). Using the collected data (Table 3), the radial velocity curve of Epsilon Herculis was constructed, as shown

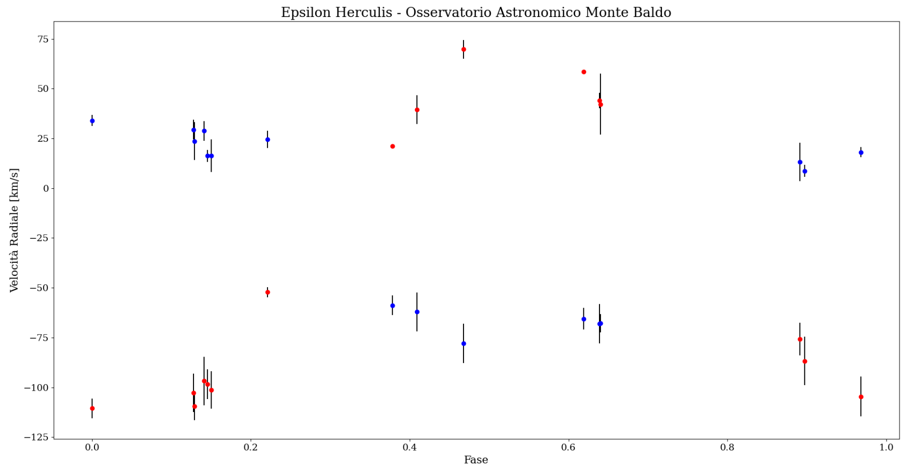

Figure 2 *: Some spectra of the Epsilon Herculis system taken from the database of the Monte Baldo Astronomical Observatory*

in Figure 2. A comparison with the curve obtained by Robert H. Baker (1910) demonstrates good convergence of the data obtained.

The radial velocity curve allows determining the spatial arrangement of the stars in the system. Existing models can be utilized for this purpose. Komonjinda (2008) proposes three different models based on the shape of the radial velocity graph.

Analyzing the graph in Figure 2, it is noted that the intersection point of the two curves (red and blue) is at approximately (-25 ± 6.6) km/s, in excellent agreement with the proper motion of the system reported in SIMBAD, Wenger et al. (2000), which is -25.1 km/s. Additionally, the most negative radial velocity, corrected for the proper motion, is -140 km/s (red curve-25), while the maximum specular value on the same day, corrected for the proper motion, is 8.4 km/s. This indicates that where Vr_2 has the highest absolute value, Vr_1 has the lowest absolute value. This model agrees with the one proposed by Komonjinda (2008). The physical model is thus depicted in Figure 3, which shows that the center of mass is located within the more massive star.

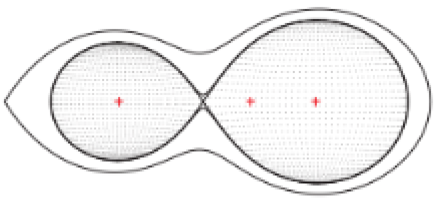

Figure 3 *: Candidate model for the Epsilon Herculis system (image taken from Komonjinda 2008)*

3.1.2 Low-Resolution Spectroscopy

The low-resolution spectra obtained (see Table 4) and shown in Figure 4 clearly display the hydrogen absorptions (Balmer series) and the D1 and D2 doublet of Na I, as well as a hint of Fe I at 5077 Å and Mg II at 5915 Å, which are not typical for A-type spectral stars.
As proposed in section 3.1.1, the system could consist of a more massive A0 spectral class star and a less massive lambda Bootis (Lam Boo) type star with A spectral class. This is deduced from the presence of metals such as Mg II, Fe I, and Fe II (among others), as also presented by Paunzen & Heiter (2014). To confirm this theory,

JD	spectrograph	calibration standard
2459789.82	MARK II	Vega
2459793.35	Alpy600	HR6677
2459797.35	LHIRES III - 600 ll/mm	HR6388
2459801.32	LHIRES III - 600 ll/mm	HR6388

Table 4 *: Setup of low and medium-resolution spectra collected by the Monte Baldo Astronomical Observatory*

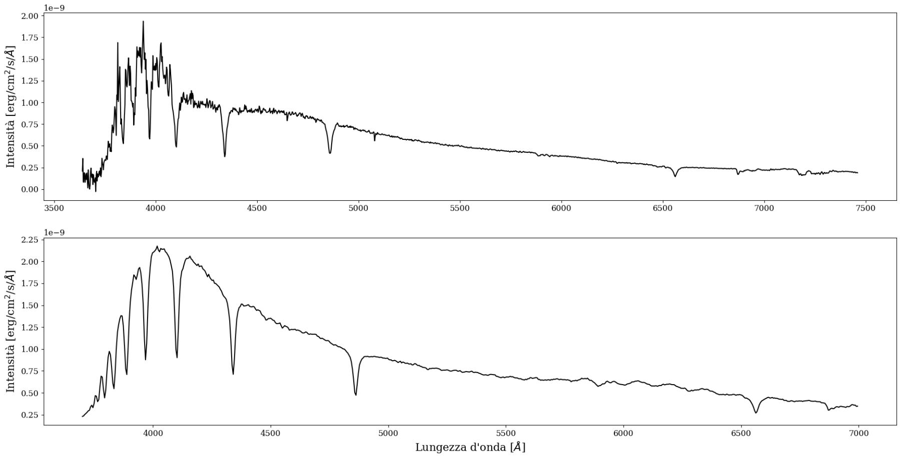

Figure 4 *: Low-resolution spectrum obtained from the Monte Baldo Astronomical Observatory using the LHIRES III spectrograph with a 600 ll/mm grating of the Epsilon Herculis system.*

medium-resolution spectra were taken (Table 4) using the SHELYAK LHIRES III spectrograph with a 600 ll/mm grating in the 4200-4900 Å range, as shown in Figure 5, to verify the presence of typical Lam Boo metals. The spectrum appears to exhibit:
Fe I: 4545.813; 4181.754; 4219.360; 4260.473; 4383.544
Mg II: 4481.126+4481.325
Fe II: 4233.172; 4522.634; 4555.893
Notably, there is strong absorption of Mg II and weak absorptions of Fe I and Fe II.

3.2 HIP107162

HIP107162, also known as 77 Cyg*, is a binary system located in the constellation of Cygnus at a distance of 412 light-years, with a magnitude of 5.73 in V.

3.2.1 High-Resolution Spectroscopy

In Table 5, similar to the previous table, the Julian date of the observations is provided, followed by the phase. The average radial velocities of both stars are then indicated along with their respective errors. Figure 8 displays three spectra of the Epsilon Herculis binary system taken at different phases, allowing us to deduce the orbital motion of the system. The presence of one or two peaks is determined by the position of the stars during the spectroscopic observation. A single peak corresponds to both stars being in line with the observer, as in the previous case. in Figure 6, the graph exhibits symmetry with respect to the vertical axis and mirror symmetry with respect to the horizontal axis.
The graph represents the radial velocity curve of the HIP107162 system, which was developed using the data provided in Table 5. The curve was compared with the one by Heyne et al (2019) to verify its accuracy. Subsequently, it was compared with the models proposed by Komonjinda (2008), showing excellent agreement with the physical

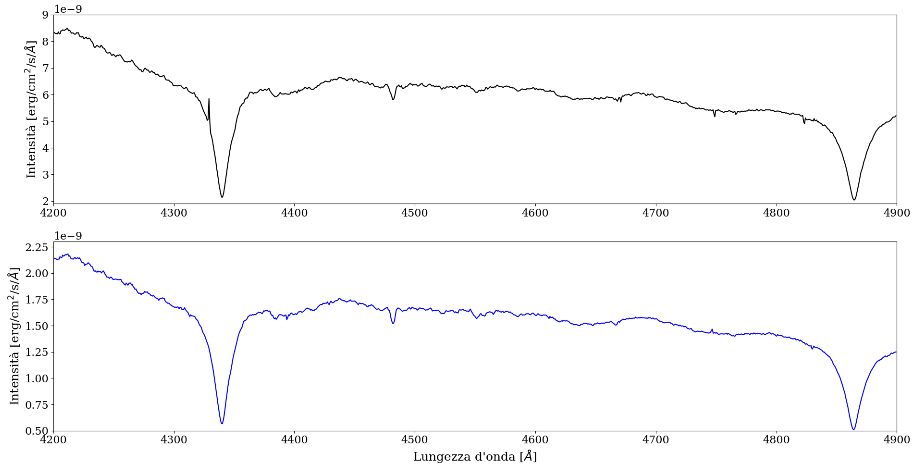

Figure 5 *: Low-resolution spectrum obtained from the Monte Baldo Astronomical Observatory using the LHIRES III spectrograph with a 600 ll/mm grating of the Epsilon Herculis system.*

JD	phase	$< Vr_1 >$	σ_{Vr_1}	$< Vr_2 >$	σ_{Vr_2}
2459755,51	0	-25,5	11,8	37,3	4,5
2459761,48	0,453	66,2	0,4	-123,7	7,2
2459763,558	0,655	-23,4	2,3	-23,4	2,3
2459768,524	0,527	63,9	5,4	-72,8	5,5
2459769,523	0,105	-10,6	3,2	-12,7	0,3
2459770,535	0,69	-36,6	2,7	35,6	4,9
2459773,488	0,398	106,2	7,8	-104,2	5,5
2459774,487	0,976	-85,8	7,3	85,3	4,3
2459776,575	0,183	26,3	2,7	-44,0	5,9
2459777,527	0,734	-79,5	7,6	49,4	9,5
2459778,433	0,258	64,2	4,6	-105,2	0,3
2459781,542	0,056	-15,7	2,7	6,4	2,8

Table 5 *: Calculated radial velocity values for the binary system HIP107162*

system depicted in Figure 7. This comparison led to the conclusion that it is a binary system with the center of mass located outside the two stars.
It can be observed that the intersection point of the two curves is at -20±6.6 km/s, which falls within the calculated average error (Section 3.3 of Komonjinda 2008) and is comparable to the intrinsic velocity of the system reported in SIMBAD by Wenger et al (2000) as -24.5 km/s

3.3 Low resolution spectroscopy

JD	spectrograph	calibration standard
2459789.82	MARK II	Vega

Table 6 *: Setup of low resolution spectra of HIP107162*

The spectrum appears characteristic of a type A star (Figure 10), as it exhibits the Balmer absorptions and the D1 and D2 absorptions of sodium; Na I (5072 Å) and Na II (4646 Å).

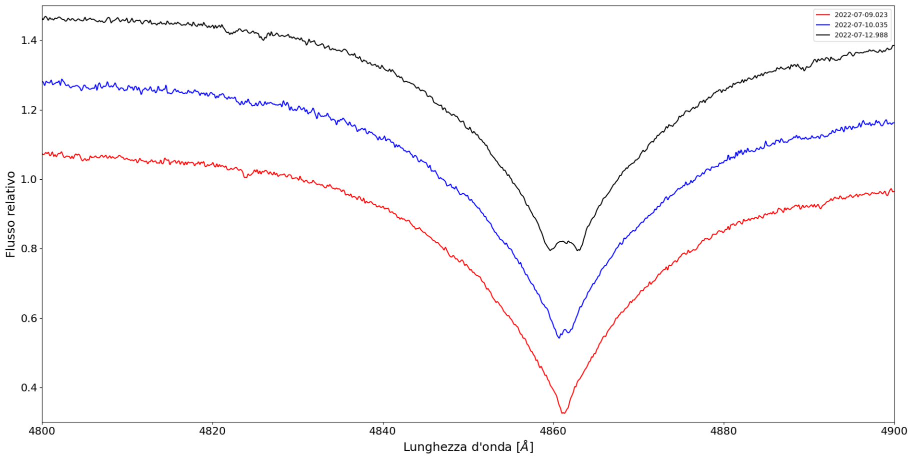

Figure 6 *: Some spectra of the HIP107162 system taken from the database of the Monte Baldo Astronomical Observatory.*

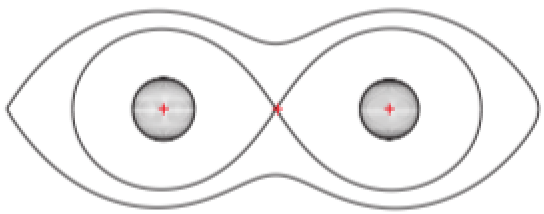

Figure 7 *: Candidate model for the HIP107162 system (image taken from Komonjinda 2008)*

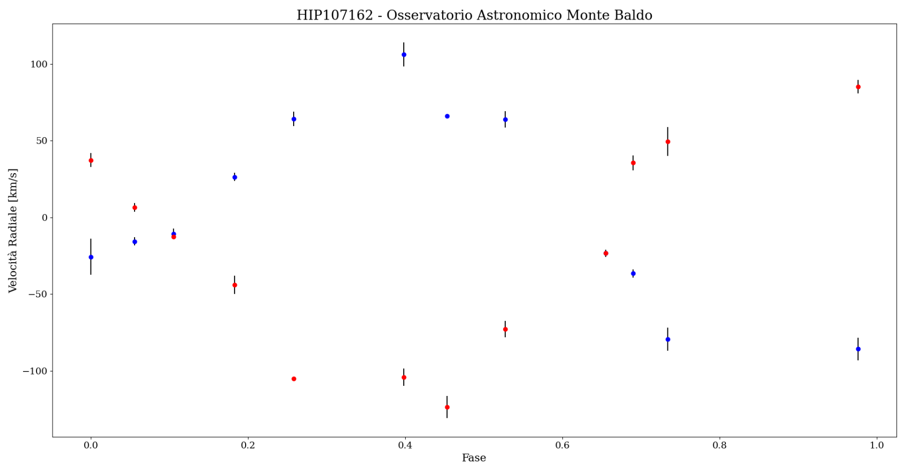

Figure 8 *: Radial velocity curve of the Epsilon Herculis binary system*

3.4 Error Propagation Analysis of Radial Velocity

All spectra were processed by the students who participated in the internship. For each spectrum, each student reported the wavelength they deemed most accurate for calculating the radial velocity using Equation 2. This allowed us to average out the systematic error introduced by each student's measurement. Additionally, the ± 1 pixel error in wavelength calibration was neglected in this case. With this approximation, the root mean square

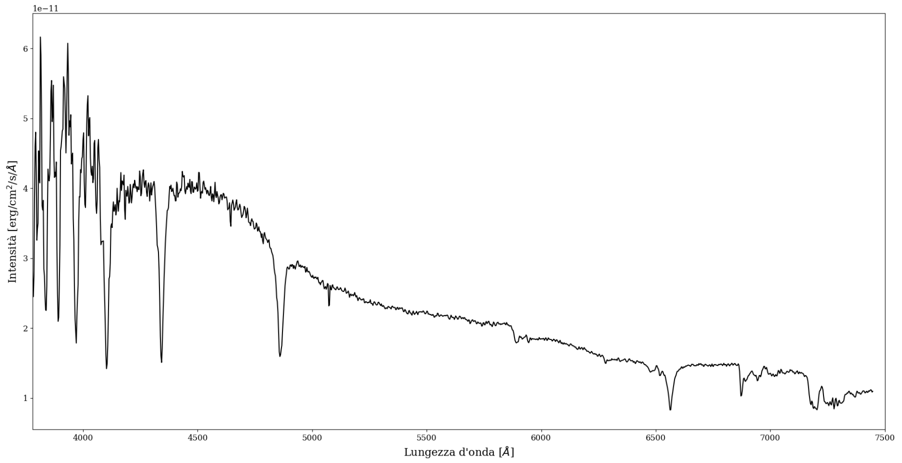

Figure 9 *: Low-resolution spectra obtained from the Stroncone Observatory (MPC589) with the MARK II spectrograph; spectra listed in Table 6.*

error (Equation 3) was used to calculate the error in radial velocity instead of the partial derivatives technique.

$$\sigma = \pm\sqrt{\frac{\sum_{n=1}^{3}(Vr_n - < Vr >)^2}{N}} \tag{3}$$

The average error of all calculated sigmas is 6.6 km/s, which is consistent within 2 km/s with the value already calculated by Andreoli & Castellani (2021; unpublished article) in another work on the radial velocities of Cepheids. Based on statistical analyses of the spectral resolution, certain spectra from the Monte Baldo Observatory (OMB) database were excluded from consideration. This decision was made because their resolution was insufficient to provide adequate analysis, particularly those with $RMS \quad >> \ < RMS >$.

4 Conclusions

We have obtained and analyzed the spectra of the two binary systems, Epsilon Herculis and HIP107162, to derive the radial velocity curves, which were subsequently compared with those of Komonjinda (2008).
Regarding the Eps Her binary system, we have determined that the two stars have different masses, with the center of mass located within the more massive star. The systemic proper motion we found is -25 m/s.
Both stars are of spectral class A, and the less massive star is likely of the Lambda Bootis type, as indicated by the analysis of low and medium-resolution spectra, which revealed the presence of elements such as Fe I, Mg II, and Fe II, typical of these stars (Section 3.1.2).
The HIP107162 system consists of two similar stars, with the center of mass located near the midpoint between the two stars. The systemic proper motion we found is -20 km/s. The low-resolution spectrum exhibits typical absorptions of an A-type star, including the Balmer series, D1 and D2, and other Na I and Na II absorptions.

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