

## SPECTROSCOPIC BINARIES IN THE LARGE MAGELLANIC CLOUD

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### RESUMEN

Estamos desarrollando un programa de observaciones de largo alcance destinado a la búsqueda de binarias espectroscópicas entre las estrellas más brillantes y tempranas de ambas Nubes de Magallanes, con el propósito de mejorar nuestro conocimiento de los parámetros fundamentales para esas estrellas y compararlos con determinaciones similares efectuadas en nuestra Galaxia. El proyecto comprende la obtención de imágenes CCD directas y espetrales desde los observatorios de CASLEO (San Juan, Argentina), La Plata (Argentina) y CTIO (Chile). Aquí presentamos resultados para 5 estrellas en la Nube Mayor de Magallanes, incluyendo: a) una nueva determinación de parámetros orbitales para Sk –67°105, una binaria espectroscópica de tipo O4f+O6:V, que presenta además variaciones de luz; b) la primera órbita de velocidad radial para Sk –66°35, una supergigante azul en la región H II gigante N11; c) el descubrimiento de una nueva binaria eclipsante de líneas dobles en la asociación OB LH 4; d) mediciones de velocidad radial para Sk –67°211, una estrella de tipo O3 III, de la cual sospechamos que podría ser de naturaleza múltiple; e) mediciones de velocidad radial para Sk –71°42, una estrella de tipo B1 Ia, cuya velocidad radial es probablemente constante.

### ABSTRACT

We are performing a long-term observing program searching for spectroscopic binaries among the brightest and earliest type stars in both Magellanic Clouds, in order to improve our knowledge of the fundamental parameters of these stars to compare them with similar determinations in our own Galaxy. The project involves both spectral and direct CCD imaging which are being carried out at the observatories of CASLEO (San Juan, Argentina), La Plata (Argentina), and CTIO (Chile). We present here results for 5 stars in the Large Magellanic Cloud, including: a) a new determination of the orbital parameters of Sk –67°105, a double-lined O4f+O6:V spectroscopic binary showing light variations as well; b) the first orbital solution for Sk –66°35, a blue supergiant in the H II region N11; c) the discovery of a new double-lined eclipsing binary in the OB association LH 4; d) radial velocity measurements for Sk –67°211, an O3 III star suspected of being a multiple system; e) radial velocity measurements for Sk –71°42, a B1 Ia supergiant with probably constant radial velocity.

**Key words:** GALAXIES: MAGELLANIC CLOUDS — STARS: BINARIES — STARS: EARLY TYPE — STARS: INDIVIDUAL (SK –67°105, SK –66°35, SK –67°211, SK –71°42, LH4-231)

### 1. INTRODUCTION

Searching for binaries among the massive stars in a galaxy is important for several reasons. Among them:

- The fraction of massive binaries may show a dramatic incidence in the slope of the initial mass function (IMF) determined from star counts;

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- the stellar upper-mass limits for galaxies of different metallicities are predicted to differ, yet empirical evidence is lacking;
- the stellar upper-masses as determined from binary orbits differ by about a factor 2 from what is found by the mass-luminosity relation.

Searches for massive spectroscopic binaries are lacking for our nearest neighbour galaxies, the Magellanic Clouds. Therefore, we have started to measure the radial velocities of some of their brightest OB members.

More than 50 stars are monitored for this study, all of them counting among the brightest and earliest type Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) members. We are reporting here the present status of our knowledge of 5 of them.

This is obviously a very long term project, which needs lots of telescope time. However, some results have been attained in the about 15 years already passed since its beginning. Therefore, this paper necessarily reads like a progress report.

## 2. OBSERVATIONS

The observations obtained for this study consist of spectroscopy at different resolutions and direct imaging performed at observatories in Argentina and Chile, as described in the following paragraphs:

### • Spectroscopy

a) CTIO: Intermediate-resolution spectra for the brightest stars in this project have been obtained with the Cassegrain image tube spectrograph attached to the 1-m Yale telescope at Cerro Tololo Inter-American Observatory (CTIO), Chile. These observations were recorded on Kodak III-aJ photographic plates prior to 1985, and with the Shectman/Heathcote two-dimensional photon-counting detector (2DF) thereafter.

b) CASLEO: Most of the observing for this program is regularly performed at the Complejo Astronómico El Leoncito (CASLEO)<sup>6</sup>, San Juan, Argentina, using the 2.15-m Jorge Sahade telescope. Two spectrographs are currently used there, namely: the REOSC échelle spectrograph for high-resolution spectroscopy ( $R \sim 14000$ ) with a  $1024 \times 1024$  Tek CCD as detector, and the Boller & Chivens Cassegrain spectrograph for intermediate-resolution observations using as detectors a  $384 \times 586$  EEV 8605 CCD from 1991 to 1994, and a  $512 \times 512$  PM CCD since 1996.

### • Direct Imaging

a) CTIO: CCD images were obtained through Kron-Cousins *VRI* filters with the camera attached to the 1-m Yale telescope at CTIO during 1984, November, using a  $388 \times 576$  GEC chip as detector.

b) CASLEO: Direct images through Johnson *UBV* filters for the fields of studied stars were obtained with the 2.15-m Jorge Sahade telescope and the  $1024 \times 1024$  Tek CCD as detector.

The observations were processed and analyzed with IRAF routines. Photographic spectra were digitized at La Plata Observatory with a Grant micro-densitometer, and then analyzed with IRAF software.

## 3. RESULTS

Here we will briefly discuss some results for 5 stars in the project, namely: Sk-67°105, Sk-67°211, Sk-66°35, Sk-71°42 and a newly discovered double-lined eclipsing binary in the LH 4 stellar association.

### 3.1. The O-Type Double-Lined Binary Sk-67°105 Revisited

Sk-67°105 (Sanduleak 1970), the exciting star of the H II region N50 (Henize 1956), (DEM 193, Davis, Elliott, & Meaburn 1976), was found to be a double-lined binary by Niemela & Morrell (1986). They classified the binary components as O4f and O6:V and derived an orbital solution with a period of 3.301 days yielding minimum masses of 41 and  $26 M_{\odot}$  for the binary components. Afterwards, light variations of this system were detected by Haefner, Simon, & Fiedler (1994), suggesting an inclination of 71°5, this resulting in masses

<sup>6</sup>CASLEO is operated under agreement between CONICET-SECyT and the National Universities of Córdoba, La Plata, and San Juan, Argentina.

of 47 and  $30 M_{\odot}$ , rather lower than those expected from their luminosities, as noticed by the same authors by placing the component stars on a theoretical H-R diagram obtained from model calculations by Schaefer et al. (1993). Haefner et al. (1994) also suggested that a slightly longer period for the binary motion would better fit the observed light variations. Direct imaging obtained at CTIO (1984) and CASLEO (between 1994 and 1997) allowed us to confirm those light variations and also the 3.301 d period while a wide set of spectroscopic observations that spread from 1983 to 1997 was used to derive a best period of  $3.3015 \pm 0.0002$  d, very well fitted by both radial velocity and photometric observations. No significant difference appears between the newly derived orbital parameters and those presented in our previous investigation of this star, thus the disagreement between the masses expected (from the mass-luminosity relation) and empirically determined (via orbital solution) remains an open question regarding this binary system.

A radial velocity orbit of Sk  $-67^{\circ} 105$  is shown in Figure 1 while light variations in the  $V$  filter are plotted in Figure 2 as a function of the improved ephemeris: HJD 2,445,384.614 + 3.3015  $E$ .

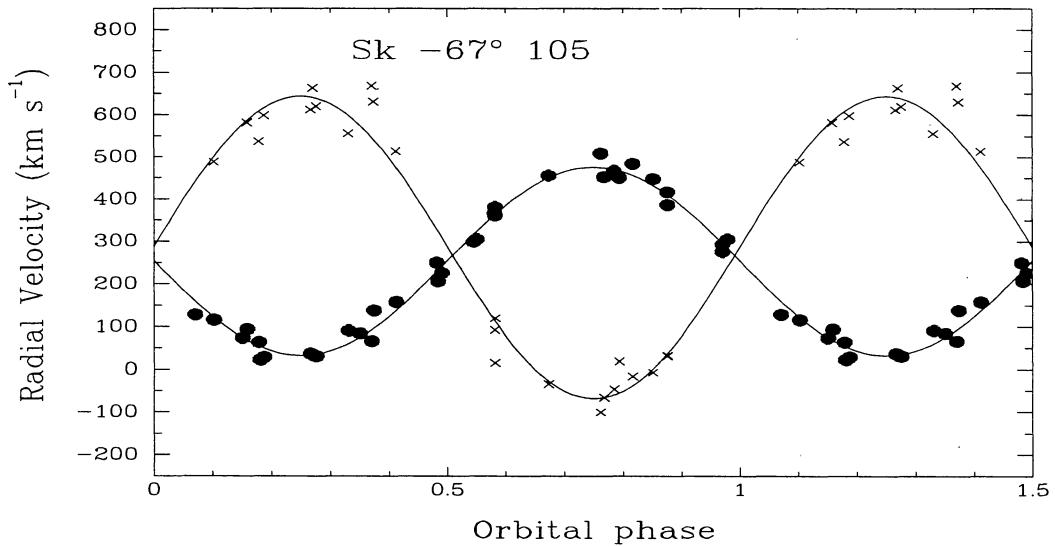


Fig. 1. Radial velocity variations of Sk  $-67^{\circ} 105$ .

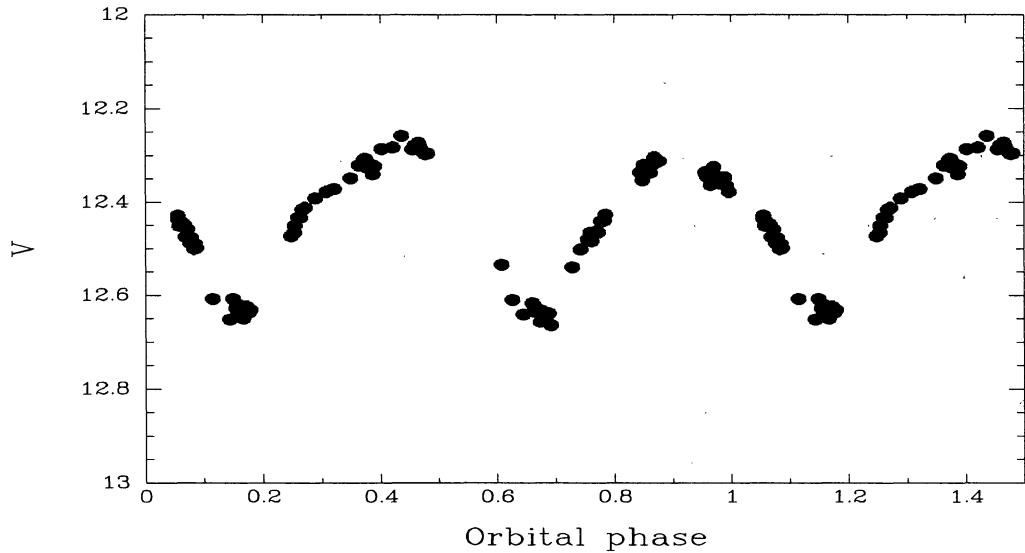


Fig. 2. Light variations of Sk  $-67^{\circ} 105$  in the  $V$  filter as a function of the improved ephemeris.

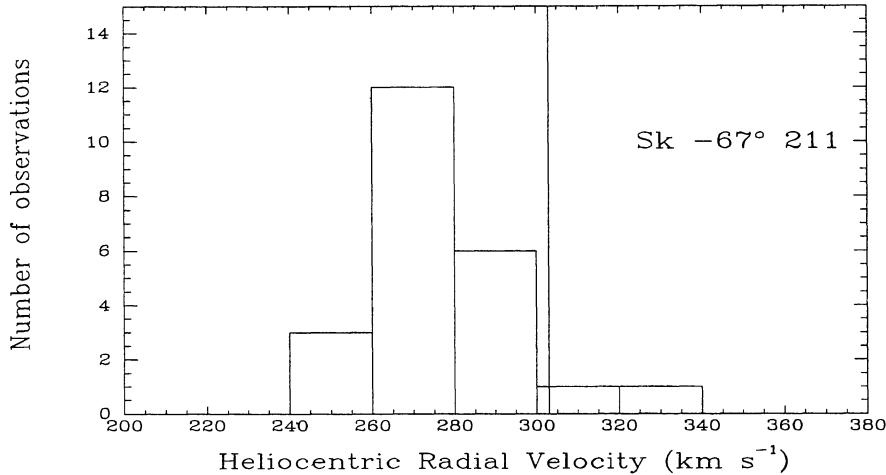


Fig. 3. Distribution of our radial velocity measurements for Sk -67° 211. The radial velocity derived for the surrounding nebula is represented as a vertical line.

In the analysis of direct CCD images of the field around Sk -67° 105, a new group of OB stars was found surrounding this binary system and thus forming a young cluster or association having Sk -67° 105 as its brightest member. Further spectroscopic investigation of the OB members in this group is in progress.

### 3.2. Sk -67° 211: Candidate to be One of the Most Massive LMC Members

Sk -67° 211 (= HDE 269810 = R 122) is a member of the association LH 82. It was classified as O3 III(f) by Walborn (1982). Model atmosphere calculations reported by Puls et al. (1996) predict for this star a mass of  $163 M_{\odot}$ , which would make it one of the most massive objects known. Considering the obvious interest of searching for radial velocity variations in this star, which, if found, could lead to an empirical mass determination, we decided to include it in our program. At the moment, from 23 spectroscopic observations suitable for radial velocity determinations, we find only marginal evidence of variations: a) a rather high scatter in the radial velocity measurements, which might also be produced by the strong stellar wind of this extremely hot star, and b) an average radial velocity which is blue-shifted relative to that of the surrounding nebula, which might also be a signature of the expanding atmosphere.

Figure 3 shows the distribution of our heliocentric radial velocities of Sk -67° 211 as derived from He II absorption lines, arranged in  $20 \text{ km s}^{-1}$  bins. As described above, no conclusive evidence is yet present to prove or rule out the binary status of this interesting object.

### 3.3. Sk -66° 35 = HDE 268732: The First Radial Velocity Orbit of a B1 Ia in N11

The blue supergiant Sk -66° 35 was classified as B1 Ia by Fitzpatrick (1988). It is located in the H II region N11 (Henize 1956) near the eclipsing binary HV 2241. Radial velocity variations for this star were reported by Niemela et al. (1996) on the base of 21 spectroscopic observations showing large scatter and a distribution characteristic of high-eccentricity binary motion. After adding about 50 new data to our records, we were able to derive a preliminary orbital solution for Sk -66° 35 with a 207 days period and the orbital elements listed in Table 1.

Figure 4 shows the observed radial velocities of this star folded with the period of 207 days, along with the best orbital fit obtained through the application of Bertiau's code (Bertiau & Grobben 1968) to our high-resolution observations only. Low-resolution observations were used in the period search, and are also represented in Fig. 4, for comparison purposes.

We note a good agreement between the derived systemic radial velocity and the radial velocity of the surrounding nebula ( $\sim 290 \text{ km s}^{-1}$  from our high-resolution observations). From the CCD photometry, light variations of the order of 0.05 magnitudes have been detected as well.

TABLE 1  
PRELIMINARY ORBITAL ELEMENTS OF SK  $-66^{\circ}35$

$P$	$= 207 \pm 1$ days	$;$	$a \sin i$	$= 222 \pm 16$ $R_{\odot}$
$K$	$= 58 \pm 3$ $\text{km s}^{-1}$	$;$	$e$	$= 0.34 \pm 0.05$
$T_0$ (HJD)	$= 2,449,734 \pm 5$	$;$	$\omega$	$= 3^{\circ} \pm 7^{\circ}$
$T_m$ (HJD)	$= 2,449,733 \pm 5$	$;$	$f(M)$	$= 3 \pm 1$ $M_{\odot}$
$\gamma$	$= 307 \pm 2$ $\text{km s}^{-1}$	$;$	Fitting Prob. Error	$= 4 \text{ km s}^{-1}$

$T_0$ : time of periastron passage.  $T_m$ : time of maximum radial velocity.

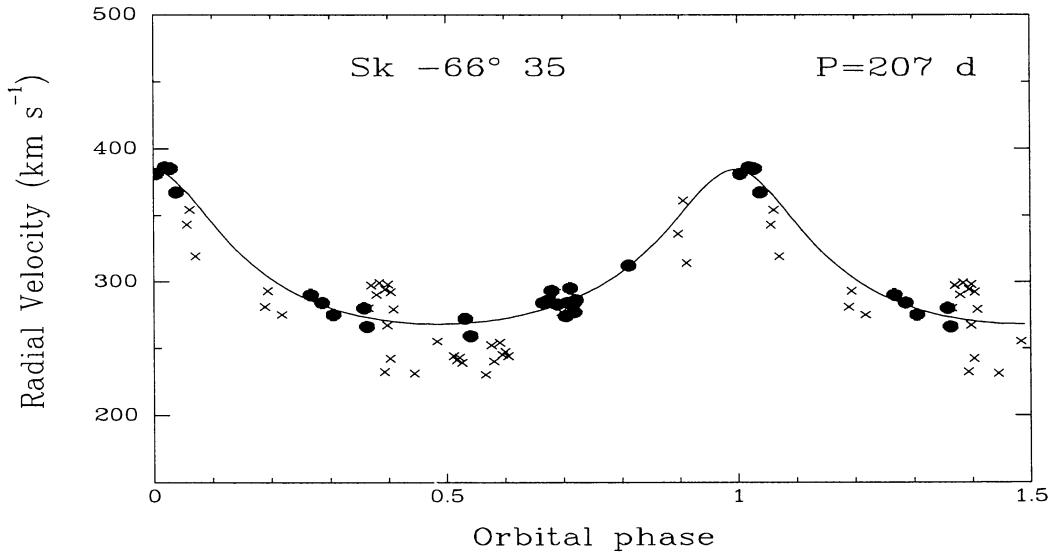


Fig. 4. Preliminary orbital fit to the radial velocity variations of Sk  $-66^{\circ}35$ . Filled circles represent high-resolution observations; crosses represent low-resolution observations. The solid curve represents the orbital solution presented in Table 1.

#### 3.4. A New Double-Lined B-Type Eclipsing Binary in LH 4

In the course of our CCD imaging to search for light variations among the brightest MC members, several fainter variables have been detected. One of them was found to be a  $\sim 4$  days period eclipsing binary displaying also double lines in its spectrum.

This star, referred to as LH 4-231 in the photometric study by Hill, Madore & Freedman (1994), is located in the stellar association LH 4 (Lucke & Hodge 1970) (=NGC 1731=N4, Henize 1956), related to the supernova remnant SNR 0453-66.9 (Chu 1997), near Sk  $-66^{\circ}5$ . Figure 5 shows a finding chart for this binary as seen in one of our  $V$  frames.

Spectroscopic observations performed in August 1997 (shown in Figure 6) revealed the double lined nature of this system which we classified as B0-1 III-V being both components similar in brightness and spectral type. Further investigation in order to derive improved spectral types and preliminary radial velocity and light curve analysis for this system is in progress.

#### 3.5. Sk $-71^{\circ}42$ : A Star with Possibly Constant Radial Velocity

Sk  $-71^{\circ}42$  (=HDE 269660=R 112) is one of the brightest members of the stellar association LH 69 (NGC 2018) in the H II region DEM 221 (N206). It was classified as B2 Ia by Fitzpatrick (1988). Radial velocity determinations performed by Feast, Thackeray, & Wesselink (1960) reported a velocity of  $237 \text{ km s}^{-1}$  for this

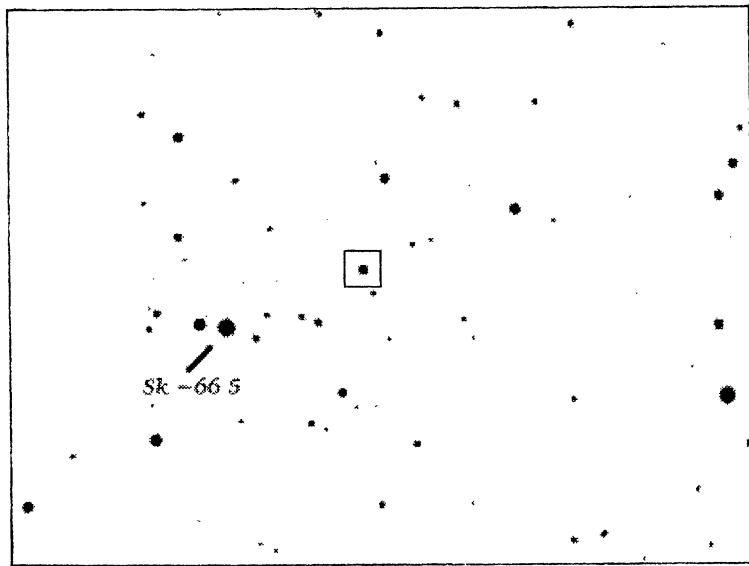


Fig. 5. Finding chart for LH 4-231, shown within a box. For reference, also the location of Sk  $-66^{\circ}5$  is indicated. North is up and East to the left, and the size of the chart is about  $5 \times 4$  arcmin.

star. A similar value ( $231 \text{ km s}^{-1}$ ) was found by Ardeberg et al. (1972). Our radial velocity measurements of 25 spectra of Sk  $-71^{\circ}42$  yield an average of  $237 \pm 13 \text{ km s}^{-1}$  (s.d.), this resulting in a probable constant radial velocity nature of this object. The same average velocity is found for the emission lines of the surrounding nebula.

#### 4. SUMMARY

We have presented here some new results from our on-going program devoted to the search and study of binary systems among early type stars in the Magellanic Clouds. In this paper we reported our progress in studying 5 LMC members, including:

- a new study of Sk  $-67^{\circ}105$  giving for this double-lined O-type system an improved ephemeris with a period of  $3.3015 \pm 0.0002$  days;
- radial velocities of the O3 III(f) star Sk  $-67^{\circ}211$  in LH 82 showing marginal evidence of variations;
- the first orbital fit to the radial velocity variations of Sk  $-66^{\circ}35$ , a B1 Ia type star in the N11 region;
- the discovery of a double-lined eclipsing binary of B-type components in the stellar association LH 4;
- new observations of the blue supergiant Sk  $-71^{\circ}42$  in LH 69 showing excellent agreement with early measurements by Feast et al. 1960, which points to a constant radial velocity for this object.

As already stated, this study is far from complete, it requires lots of observing time and would benefit from larger aperture telescopes in order to improve its efficiency. In spite of these inconveniences, we believe that even partial results are relevant if we want to compare the mass-luminosity relation for massive stars in our Galaxy and our close neighbours the Magellanic Clouds.

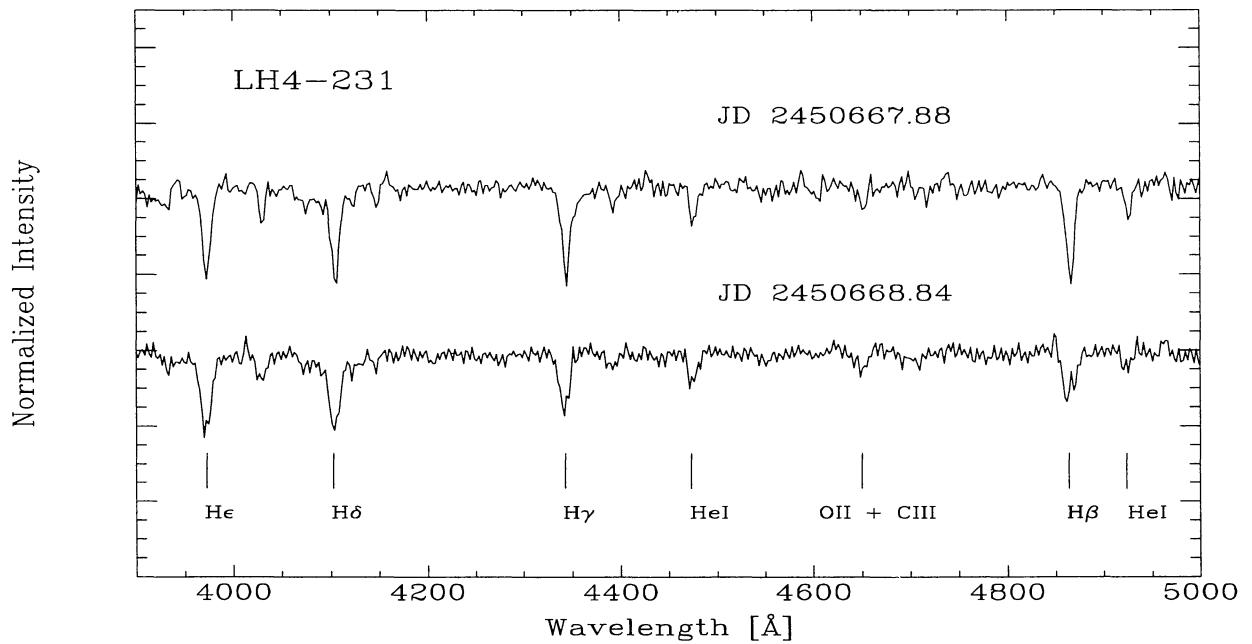


Fig. 6. CCD spectral observations of LH 4-231 obtained in two consecutive nights. Double lines are observed at HJD 2,450,668.84, with a velocity separation of  $\sim 550 \text{ km s}^{-1}$  between the binary components.

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#### REFERENCES

Ardeberg, A., Brunet, J.-P., Maurice, E., & Prevot, L. 1972, A&AS, 6, 249  
 Bertiau, F. C., & Grobben, J. 1968, Ric. Astron. Spec. Vat., 8, 1  
 Chu, Y.-H. 1997, AJ, 113, 1815  
 Davis, R. D., Elliott, K. H., & Meaburn, J. 1976, Mem. RAS, 81, 89  
 Feast, M. W., Thackeray, A. D., & Wesselink A. J. 1960, MNRAS, 121, 337  
 Fitzpatrick, E. L. 1988, ApJ, 335, 703  
 Haefner, R., Simon, K. P., & Fiedler, A. 1994, A&A, 288, L9  
 Henize, K. G. 1956, ApJS, 2, 315  
 Hill, R. J., Madore, B. F., & Freedman, W. L. 1994, ApJS, 91, 583  
 Lucke, P. B. & Hodge, P.W. 1970, AJ, 75, 171  
 Niemela, V. S., & Morrell, N. I. 1986, ApJ, 310, 71  
 Niemela, V. S., Morrell, N. I., Bosch, G. L., & Barbá, R. H. 1996, in ASP Conf. Ser. Vol., 90, The Origins, Evolution, and Destinies of Binary Stars in Clusters, ed. E. F. Milone & J. C. Mermilliod (San Francisco: ASP), 224  
 Puls, J. et al., 1996, A&A, 305, 171  
 Sanduleak, N. 1970, Contr. of CTIO, 89  
 Schaerer, D., Meynet, G., Maeder, A., & Schaller, G. 1993, A&AS, 98, 523  
 Walborn, N. R. 1982, ApJ, 254, L15