POLARIMETRIC DETERMINATION OF SPATIAL ORBITAL ORIENTATION OF THE BINARY SYSTEMS γ_1 AND γ_2 VEL

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RESUMEN. Por medio de observaciones polarimétricas se han estimado las orientaciones espaciales de las órbitas de los sistemas interactuantes γ_1 y γ_2 Velorum. Observaciones realizadas en las regiones espectrales de los filtros v e y de Stromgren y B y V de Johnson, mostraron variaciones periódicas de la polarización lineal con respecto a la fase orbital de acuerdo a las que predicen los modelos con dispersión Thomson en las envolturas de los sistemas binarios interactuantes. Ajustando las observaciones a los modelos, se han calculado las inclinaciones, las orientaciones de las perpendiculares a las órbitas y el sentido de giro de los dos sistemas. La posibilidad de que ambas órbitas sean coplanares se discute brevemente en base a estos parámetros. γ_2 Vel fue también observada en las regiones espectrales de las líneas de emisión lo cual permitió estudiar la distribución espacial de la atmósfera extendida de este sistema de tipo Wolf-Rayet.

ABSTRACT. Models on circumstellar polarization in close binary systems have been used to estimate the spatial orientations of the orbits of γ_1 and γ_2 Vel. Observations made in Johnson B, V filters and Stromgren v, y filters have shown polarimetric phase variations of the double-locked type such as those predicted by models with Thomson scattering in a circumstellar envelope. The variations were adjusted to the models which provide the inclination of the orbital plane, the orientation of the normal to the orbit and the sense of revolution of each system. The possibility of coplanarity between the orbits of γ_1 and γ_2 Vel is considered. γ_2 Vel has also been observed in the line emission spectral regions. The data allowed to infer the structure of the extended atmosphere of this Wolf-Rayet binary system.

I. INTRODUCTION

It is generally accepted that the linear polarization detected in several close binary systems is a product of light scattering by the electrons present in their envelopes. The polarization of the total emergent flux depends on the direction to the observer, resulting in a periodic variation about the orbital cycle. Detailed models on electron scattering in a co-rotating, optically thin, circumstellar envelope predict first and second order harmonic variations of Q and U Stokes polarimetric parameters (Brown, McLean and Emslie 1978, Rudy and Kemp 1978). The coefficients of the Q and U Fourier series depend on three orbital elements which can be derived: the inclination of the orbital plane, the sense of revolution of the system and the orientation in the sky of the normal to the orbital plane. Several close binary systems have displayed double-locked polarimetric phase variations and their orbital parameters could be obtained (Rudy and Kemp 1976, 1977, 1978, McLean 1980, Luna 1982).

Since 1978 we have been carrying out from La Plata Observatory a project to search for variable linear polarization in a sample of southern close binary systems. One of our purposes is to obtain the orbital parameters in those systems which show double-locked phase variations. The survey include some early type systems belonging to stellar agreggates which allow to compare the orbital orientation of the group members. The question of coplanarity between them can be evaluated. Using polarimetric data of three binary systems of the Sco OB1 association we have made an analysis of this kind (Luna 1983). In the present paper we will show the results on γ_1 and γ_2 Velorum. These two spectroscopic binary systems apparently belong in a group of a few other stars (Abt *et al.* 1976) and may be gravitationally bound. Both systems show evidence of circumstellar envelopes: γ_2 Vel (spectral type WC8+O9I) is the brightest Wolf-Rayet in the whole sky, with an orbital period of 78 days; γ_1 Vel (spectral type B2III) displays large scatter in the radial velocity measurements which yield an orbital solution with a 1.48-day period (Hernández and Sahade 1980).

II. THE OBSERVATIONS

The observations were carried out during the southern summer of 1981-82 with the same polarimeter mentioned in a previous paper (Luna 1982). The polarimeter, equipped with an EMI 6094 photomultiplier, was attached to the 83-cm telescope of La Plata Observatory. γ_1 Vel has been observed using B and V standard filters while γ_2 Vel was observed in four spectral regions: the continuum with the v and y intermediate-pass band of the Strömgren photometric system (λ eff. 4100 A and 5500 A, respectively) and the emission lines of He II (λ 4686 A) and C III (λ 5696 A) with narrow pass-band filters.

The instrumental polarization have been determined in each spectral region by means of observations of the zero-polarization standard stars (Timbergen 1979): HD 43834, HD 50241 and HD 68456 for B, V, v and y filters and HD 61421 and HD 80007 for the narrow filters. The angular difference between our instrumental reference system and the equatorial system was determined for each night by observations of highly polarized standard stars, namely HD 80558 and HD 84810 (Serkowski, Mathewson and Ford 1975, Hsu and Breger 1982). This angle turned out to be 150°; it is constant within ±0$^\circ\!\!.$5.

The results of the observations of γ_1 and γ_2 Vel are shown in Table 1 and Table 2, respectively, where we have listed the normalized Stokes parameters Q and U of each observation together with their corresponding Julian Dates. The spectral regions are also distinguished. Q and U are measured in the instrumental reference system where they are defined by

$$Q = P \cos 2(\theta - 150°)$$

$$U = P \sin 2(\theta - 150°)$$

where P is the degree of polarization and θ is the orientation of the electric-field vibration in the equatorial coordinate system.

All the measurements were made so as to reach the maximum possible accuracy. The mean error of the observations is 0.04% for both Q and U. This error was obtained using an integration time of about 2 to 5 minutes for the broad and the intermediate- pass bands, and 20 to 30 minutes for the line observations.

TABLE 1

Polarimetric observations of γ_1 Vel.

JD(2440000 +)	Filter	Q(%)	U(%)	JD(2440000 +)	Filter	Q(%)	U(%)
4941,711	B	,00	+,11	4946,685	B	+,16	+,04
4941,793	B	-,15	+,10	4946,688	V	-,05	+,13
4941,715	V	-,04	+,11	4946,740	V	-,05	+,10
4941,797	V	+,03	+,02	4946,804	V	+,02	-,02
4942,683	B	-,03	+,11	4954,683	B	+,01	-,01
4942,749	B	-,09	+,08	4954,769	B	+,11	+,14
4942,798	B	-,07	+,02	4954,685	V	+,07	-,01
4942,685	V	-,07	+,08	4954,771	V	-,01	-,04
4942,751	V	-,05	+,19	4967,604	B	-,13	+,12
4942,800	V	,00	+,15	4967,738	B	-,07	+,09
4946,738	B	-,18	+,20	4967,606	V	-,06	+,07
4946,802	B	-,01	-,10	4967,676	V	+,02	+,11

TABLE 1 (continued)

JD(2440000+)	Filter	Q(%)	U(%)
4967,741	V	-,01	+,03
4975,591	B	+,06	-,01
4975,649	B	+,08	+,04
4975,722	B	-,01	,00
4975,793	B	+,01	+,08
4975,594	V	+,11	+,07
4975,653	V	+,05	+,05
4975,726	V	-,07	-,02
4975,801	V	-,03	+,07
5011,508	B	,00	+,05
5011,510	V	+,01	+,09
5015,531	B	+,06	-,08
5015,576	B	+,05	-,03
5015,615	B	+,07	+,03
5015,665	B	+,02	+,03
5015,706	B	-,01	+,08
5015,742	B	+,03	+,12
5015,781	B	+,04	+,06
5015,533	V	+,03	,00
5015,578	V	+,04	+,02
5015,618	V	+,05	+,03
5015,708	V	+,02	+,09
5015,744	V	+,08	+,08
5015,785	V	+,04	+,03
5023,538	B	+,16	+,11
5023,588	B	+,04	+,07
5023,624	B	+,13	+,09
5023,667	B	+,08	+,07
5023,539	V	+,10	+,13
5023,591	V	+,10	-,02
5023,626	V	+,10	-,07
5023,669	V	+,08	+,01
5025,536	B	+,09	+,31
5025,585	B	-,03	+,05
5025,625	B	+,05	+,02
5025,674	B	+,06	+,01
5025,718	B	+,05	+,02
5025,755	B	+,10	-,03
5025,539	V	+,08	+,22
5025,587	V	,00	-,01
5025,628	V	+,03	+,06
5025,676	V	,00	,00
5025,720	V	+,03	,00
5025,759	V	+,07	+,04
5068,566	B	-,03	-,03
5068,668	B	+,02	+,09
5068,568	V	+,07	-,05
5068,672	V	+,06	+,07
5094,460	B	-,02	+,05
5094,495	B	-,05	+,06
5094,530	B	-,01	-,02
5094,558	B	+,04	-,03
5094,464	V	-,02	+,06
5094,500	V	-,01	+,12
5094,535	V	+,05	,00
5094,560	V	+,05	+,05

TABLE 2

Polarimetric observations of γ_2 Vel.

JD	v		4686 A		y		5696 A	
(2440000+)	Q(%)	U(%)	Q(%)	U(%)	Q(%)	U(%)	Q(%)	U(%)
4941,5	-,14	-,05	+,07	+,02	+,09	+,01	-,07	+,01
4942,5	-,03	-,07	+,23	-,15	,00	,00	+,10	-,07
4946,5	+,03	-,10	+,24	-,05	-,09	-,22		
4954,5	+,12	-,01	+,17	-,02	+,12	+,15	+,17	,00
4967,5	-,16	-,06			+,07	+,07		
4975,5	+,12	+,11	+,17	-,05	+,09	-,01	+,18	-,01
5002,5	+,17	-,10	+,07	+,15	+,20	+,12	-,02	+,10
5004,5	+,29	+,14	+,05	+,04	+,23	-,02	+,06	+,02
5015,5	+,05	+,16	+,02	+,18	-,07	+,14	-,04	+,21
5025,5	+,22	+,04	+,08	+,03	+,10	-,04	+,03	+,25
5031,5	+,30	+,11	+,07	+,11	+,17	+,06	+,13	+,01
5036,5	+,20	+,03	+,12	,00	+,13	+,06	+,03	+,07
5041,5	+,18	+,03	+,08	-,02	+,05	+,13	+,05	+,13
5051,5	+,10	+,19	+,05	+,02	+,04	+,11	+,04	+,10
5058,5	-,05	+,16	+,14	-,04	+,05	-,01	+,10	-,02
5068,5			-,05	-,06	+,04	-,08		
5071,5	+,08	+,19	+,03	-,06	+,31	+,03	-,13	+,19
5089,5	+,19	-,06	+,08	+,04	+,33	+,02		
5373,5					+,03	,00		
5377,5					+,03	+,01		
5383,5					+,01	-,11		

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III. RESULTS AND DISCUSSION

1. γ_1 Velorum

Fig. 1 shows the B and V observations of γ_1 Vel versus the orbital phases. The phases were calculated from the ephemeris given by Hernández and Sahade (1980). Both spectral regions show a clear double-locked phase variation in the Q parameter. The values of the U parameter show a scatter of the same order of the errors. In this Figure the full lines were drawn with the aim of attempting to estimate the orbital orientation.

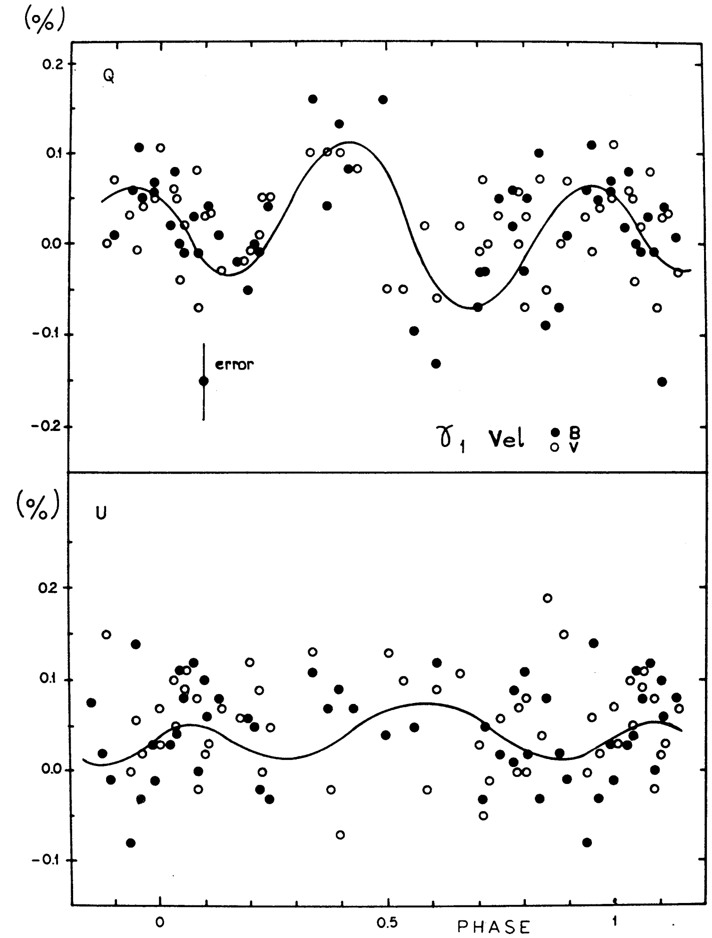

Fig. 1. Observed Q and U values vs. the orbital phase of γ_1 Vel. The filled and open circles are the B and V observations, respectively. Full lines are hand-drawn representations of the double-locked variations.

The canonical model, in which circular orbit, no eclipsing effects, and optically thin envelope are considered, predicts phase harmonic variations of first and second order such as those suggested by the full lines of Fig. 1. The full lines are plotted in Fig. 2 on the Q-U plane. The dashed trajectory represents the second order variation which was obtained by the geometrical method of Brown, McLean and Emslie (1978). The excentricity of the Q-U ellipse is given by $\sin^2 i/(1 + \cos^2 i)$, where i is the inclination of the orbital plane. The angle between the direction of the major axis and the Q axis corresponds to twice the orientation of the normal to the orbital plane projected on the sky plane. This last parameter have two possible values differing 90° from each other because there is an uncertainty of 180° in the angle of the Q-U plane. The sense of revolution of the binary system can be inferred from the Q-U trajectory.

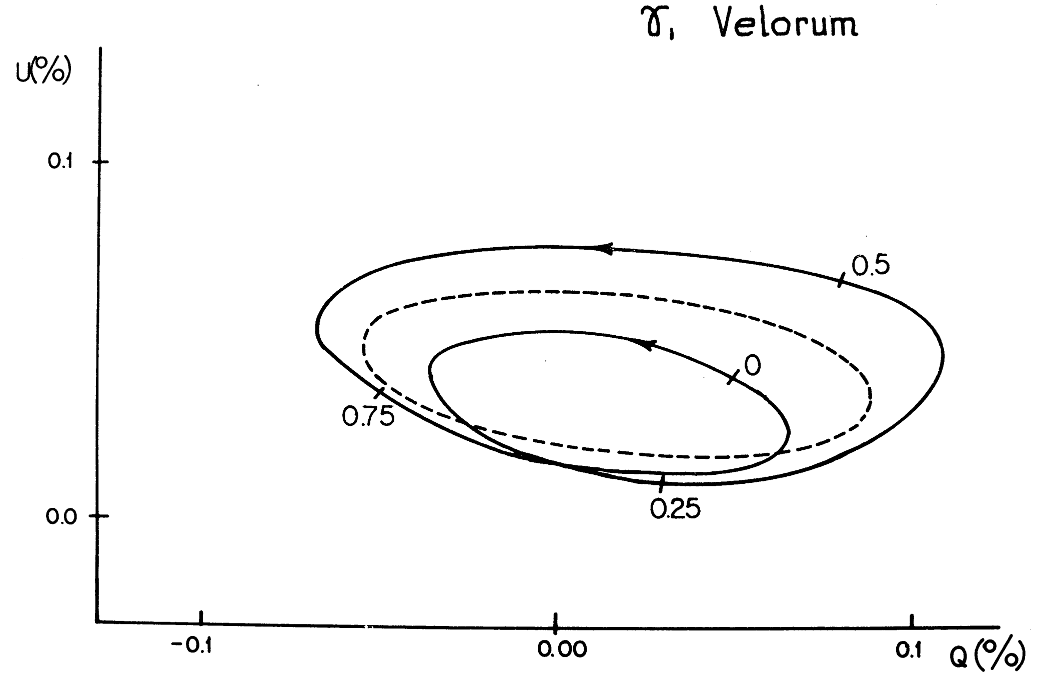

Fig. 2. The full lines of Fig. 1 plotted in the Q-U plane. The elliptic trajectory corresponds to the second order variations. The excentricity of the ellipse gives an inclination of the orbital plane of 81°.

The inclination of the orbital plane of γ_1 Vel as derived here is of 81°, the orientation of the normal to the orbit in sky plane is 86° or 176°, and the sense of revolution is counterclockwise. Due to the large uncertainties of the U variations of Fig. 1, these values have a considerable error. However, the inclination of the orbital plane cannot be lower than 75° because the amplitude of the U variation is small and in either situation the result is an ellipse of high excentricity (high inclination) in the Q-U plane. We estimated an error of ±10° for the orientation of the normal to the orbital plane.

2. γ_2 Velorum

Figures 3 and 4 show the observations made in the continuum and in the lines, respectively, versus the orbital phases. The phases were calculated from the ephemeris given by Niemela and Sahade (1980). Phase zero corresponds the instant when the O star is in front the WR component. From these figures we obtain the following genereal conclusions:

a) The polarization in both continuum regions shows a similar behaviour. The Q parameter displays a double-locked variation and the U parameter shows a scatter of the order of the errors.

b) The polarization in the C III and He II lines is lower than the polarization of the continuum regions. The scatter of the values in both Q and U is of the order of the errors.

The fact that the behaviour of the linear polarization in the continuum is not similar to those of the lines, would be understandable in terms of the structure of the WR envelopes. It is well known that a large temperature gradient produces a stratification in the formation of the emission spectrum. The high-temperature excitation lines of C III and He II are formed close to the photosphere of the WC8 component of γ_2 Vel. If the electron envelope is located around the WR component the scattering of the line emission has no preferential direction and the flux would appear depolarized. On the other hand, most of the continuum radiation comes

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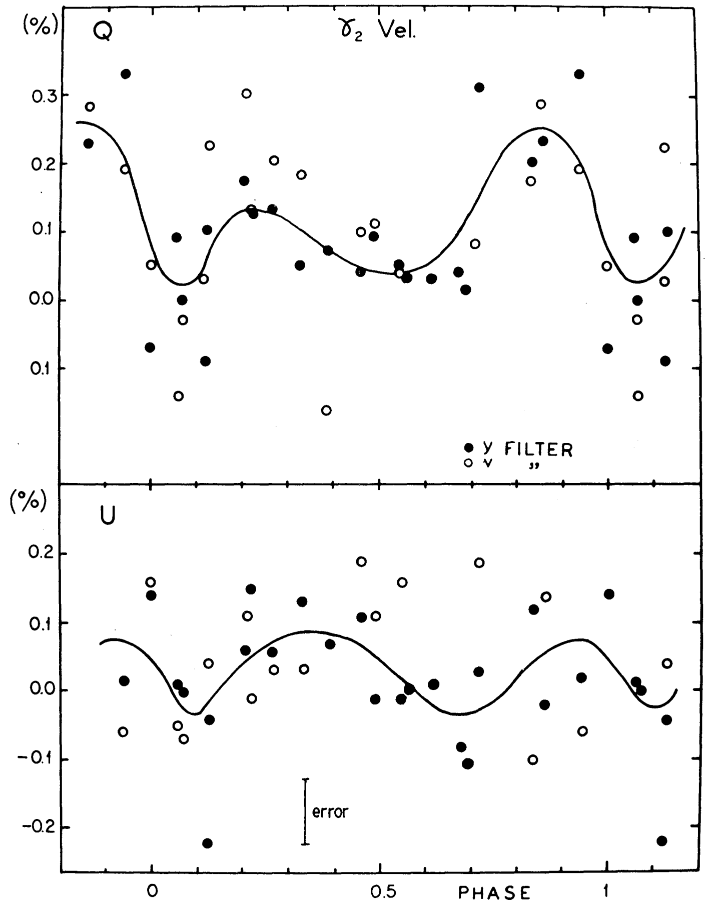

Fig. 3. Same as Fig. 1 for the continuum observations of γ_2 Vel. Filled and open circles correspond to the y and v filters, respectively. The full lines were plotted taking into account the filled circles.

from the O star and the scattering is more effective towards the WR component. Then, the flux of the continuum radiation results highly polarized. A double-locked variation about the orbital phase, such as those of Fig. 3, is originated.

We can estimate the spatial orientation of the γ_2 Vel orbit from the polarimetric phase variations of the continuum spectral regions. The full lines of Fig. 3 are tentative representations of these variations. They were hand-drawn taking into account only the y filter observations, although the v filter values also show a double-locked behaviour, more clearly in the Q parameter. Fig. 5 shows the full lines on the Q-U plane. The dashed trajectory corresponds to the second order variation which given an inclination of 80°±7° and 20° or 110°±10° for the orientation of the normal to the orbital plane. The sense of revolution is counterclockwise. The full line of the U parameter is very approximate and the uncertainties were taken into account to estimate the errors of the derived orbital parameters. Moffat (1977) found no light variations in γ_2 Vel and he estimated a maximum inclination of 73°. We conclude that the inclination is 70°-80° taking into account both the polarimetric and photometric analysis.

It must be mentioned that, contrary to the canonical model predictions, the Q full line of Fig. 3 seems to present, in addition, a third order variation, which may appear when the orbital excentricity is not around zero (Brown *et al.* 1982). The orbital excentriciy of γ_2 Vel is 0.4 (Niemela and Sahade 1980) and it may be the explanation for the presence of third order terms in the polarimetric variations. According to the theoretical results, the orientation and excentricity of the Q-U ellipse in the circular orbit model do not change in such a

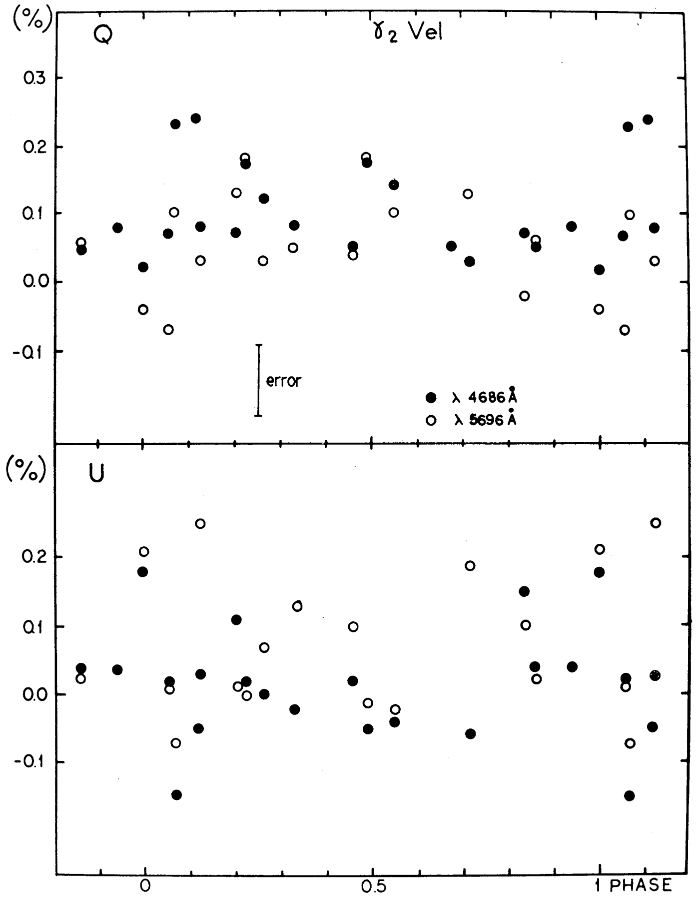

Fig. 4. The observations in the lines vs. the orbital phase of γ_2 Vel. Filled and open circles represent the observations made in He II and C III, respectively.

situation. Consequently, the orbital parameters derived above would not be affected by the orbital excentricity.

The orbital parameters of γ_1 and γ_2 Vel as well as their corresponding errors have been calculated, as indicated above, using a pure graphical method on the Q-U plane. Another method of doing this computation is a regression of Fourier series up to second order terms for γ_1 Vel and to third order terms for γ_2 Vel. The coefficients of the series are related to the orbital parameters and they can be analytically obtained (Brown, McLean and Emslie 1978). When the inclination is high both methods give comparable results and similar accuracies. According to Aspin, Simmons and Brown (1981) the accuracy of the inclination determined through a polarimetric analysis is a function of the inclination itself, being higher if the inclination is higher (see also Luna 1983). So, the inclinations of γ_1 and γ_2 Vel are determined with high accuracy, in spite of the rather noisy data. The quality of our data would not permit the determination of inclinations lower than 70° with a reasonable accuracy. In order to compare both methods we have calculated the inclinations of the orbital planes by the Fourier analysis. The series are:

$$Q = 0.018 - 0.014 \cos\phi + 0.033 \sin\phi + 0.041 \cos 2\phi - 0.059 \sin 2\phi$$

$$U = 0.041 - 0.014 \cos\phi - 0.008 \sin\phi + 0.013 \cos 2\phi + 0.018 \sin 2\phi,$$

for γ_1 Vel, and

$$Q = 0.106 + 0.043\cos\phi - 0.027\sin\phi - 0.045\cos2\phi - 0.065\sin2\phi - 0.027\cos3\phi - 0.025\sin3\phi$$

$$U = 0.030 - 0.010\cos\phi + 0.026\sin\phi + 0.004\cos2\phi - 0.045\sin2\phi - 0.004\cos3\phi - 0.015\sin3\phi ,$$

for γ_2 Vel.

The second order coefficients give an inclination of 81° for both γ_1 and γ_2 Vel. There, the orientations of the normals to the orbits projected on the sky plane, Ω, are referred to the equatorial system, i.e., this angle is measured from the North direction towards East. The relative orientation between both orbits, in particular the coplanarity, can be evaluated from these values. The sufficient but not necessary condition for coplanarity is that i and Ω be equal. Both binary systems seem to have high inclinations and similar senses of revolution. However, the minimum possible difference between the Ω's is 24°, and the errors involved are not small enough to ascertain as to whether or not the two values are coincident. We conclude that our results do not reject the possibility that the orbits of γ_1 and γ_2 Vel are coplanar.

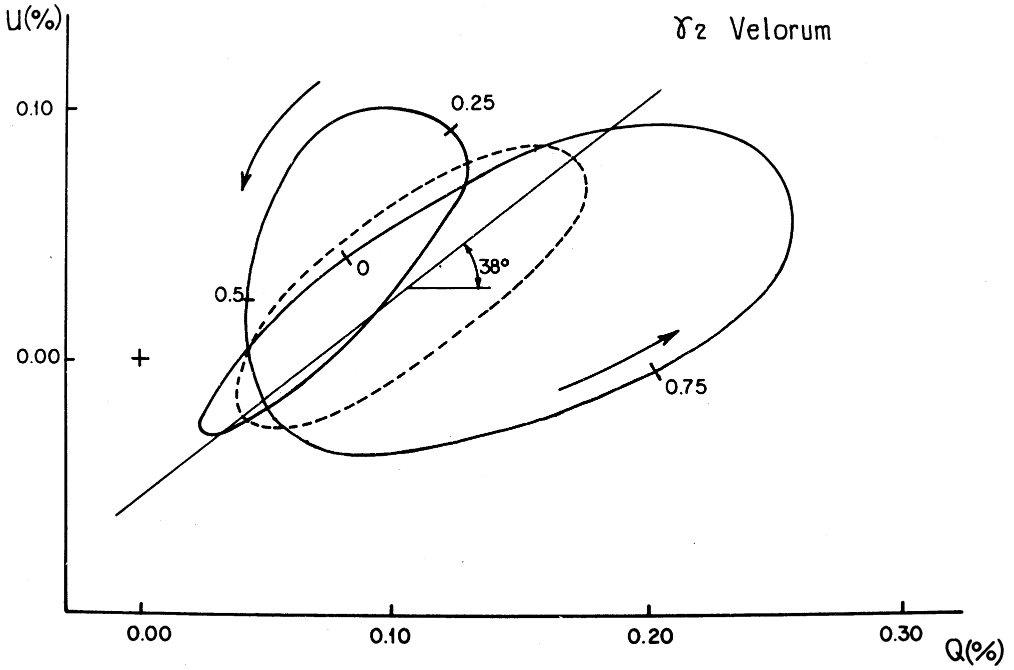

Fig. 5. The polarimetric variations of γ_2 Vel on the Q-U plane. The ellipse plotted with dashed line correspond to the second order variations and gives an inclination of the orbital plane of 80°.

TABLE 3

Polarimetric orbital parameters of γ_1 and γ_2 Vel.

	i	Sense of Revolution	Ω *
Vel	75°-90°	counterclockwise	56° or 146° ± 10°
Vel	70°-80°	counterclockwise	80° or 170° ± 10°

* The values of Ω are given in the equatorial frame of reference; they are equal to the instrumental values of Ω plus 150°, as indicated in the text.

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DISCUSSION

Peimbert: ¿Hay información sobre la pérdida de masa en estos sistemas a partir de observaciones del Satélite Ultravioleta Internacional y su posible relación con la polarización?

Luna: La polarización está relacionada con el número de electrones y no con la pérdida de masa.

Waldhausen: ¿Cómo se ha hecho para separar la componente de polarización interestelar de la componente de polarización intrínseca?

Luna: En NGC 6231 no puede ser separada la componente intrínseca de la interestelar.

Sahade: Ud. mencionó que β Lyr se parece a las O y qué de los otros sistemas B observados? ¿Porqué no dice algo respecto a la diferencia entre los sistemas que justifiquen lo que se encuentra? ¿Cuál es la incertidumbre de la inclinación?

Luna: β Lyr tiene masas relativamente mayores, por lo tanto mayor volumen y mayor número de electrones.

Maza: ¿Cuál es el error típico en las observaciones presentadas?

Luna: 0.05% en Q y U.

Niemela: Comentario: este es un único medio para determinar inclinaciones en sistemas binarios que no son eclipsantes. ¿Quisieras comentar sobre donde fueron hechas las observaciones?

Luna: Las observaciones fueron realizadas con el polarímetro del Observatorio de La Plata, utilizando el telescopio de 83 cm de La Plata y el 76 cm del Observatorio El Leoncito.

Sisteró: Hiciste estimaciones para ver si tienen alguna importancia los efectos de reflexión (fotosférica)?

Luna: Está contemplado en parte en los modelos.

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