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ECLIPSING VARIABLE STARS IN NEIGHBOURING GALAXIES
II. Discussion of the light curve of V 55 in NGC 2403

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ABSTRACT. ECLIPSING VARIABLE STARS IN NEIGHBOURING GALAXIES :

II. Discussion of the light curve of V 55 in NGC 2403

The light curve of the eclipsing variable V 55 in the spiral galaxy NGC 2403 is discussed by means of an analysis in the frequency domain in order to obtain photometric orbital elements.

The solution of the orbit shows that V 55 is a detached-type system whose components, differing very little from each other, should belong to the earlier spectral classes.

The binary system discussed here appears to be the most remote system so far discovered.

RIASSUNTO. VARIABILI AD ECLISSE NELLE GALASSIE VICINE :

II. Analisi della curva di luce di V 55 in NGC 2403

La curva di luce della variabile ad eclisse V 55 nella galassia a spirale NGC 2403 è stata analizzata, mediante tecniche di elaborazione dati che operano nel dominio delle frequenze, al fine di ottenere gli elementi orbitali fotometrici.

La soluzione orbitale ottenuta mostra che V 55 è un sistema "detached" con le componenti, poco differenti fra di loro, che dovrebbero appartenere ai primi tipi spettrali.

La binaria studiata nel presente lavoro risulta essere la più lontana variabile ad eclisse conosciuta fino ad ora.

RESUME. VARIABLES ECLIPSANTES DANS LES GALAXIES VOISINES :

II. Discussion de la courbe de lumière de la variable V 55 dans NGC 2403

La courbe de lumière de la variable à éclipses V 55 de la galaxie spirale NGC 2403 est analysée ici grâce à une méthode opérant dans le domaine des fréquences, afin d'obtenir les éléments orbitaux photométriques.

La solution orbitale montre que V 55 est un système du type "détaché" dont les composantes, qui diffèrent peu l'une de l'autre, devraient appartenir aux premiers types spectraux.

La binaire étudiée ici se trouve être la variable à éclipses la plus lointaine que l'on connaisse actuellement.

RESUMEN. ESTRELLAS VARIABLES ECLIPSANTES EN GALAXIAS CERCANAS

II. Discusión de la curva de luz de la variable V 55 en NGC 2403

La curva de luz de la variable a eclipses V 55 de la galaxia espiral NGC 2403 ha sido analizada aquí gracias a un método que opera en el dominio de las frecuencias, con el fin de obtener los elementos orbitales fotométricos.

La solución orbital obtenida muestra que V 55 es un sistema de tipo "desligada" cuyos componentes, que difieren muy poco el uno del otro, deberian pertenecer a los primeros tipos espectrales.

La binaria estudiada en el presente trabajo resulta ser la eclipsante más lejana conocida hasta ahora.

1: INTRODUCTION

The star discussed in this paper is the only eclipsing variable discovered so far in the spiral galaxy NGC 2403 which, being a member of the M81 system, is consequently outside the Local Group.

Considering the (m-M) of the galaxy, the distance of the star should be roughly:

$$11.8 \times 10^{6} \text{ light-years}$$

V55 is located in the NE part of NGC 2403, in a spiral arm of the galaxy.

2: OBSERVATIONS

The star was discovered in 1968 by TAMMAN and SANDAGE (1) during a search for cepheid variables in NGC 2403. It was found on blue plates exposed with the 506-cm telescope at Mount Palomar in view of establishing the distance modulus of the galaxy.

The observations available span an interval from 1949 to 1963.

The general data on V55 are the following:

Max. = 21.80 ± .01 mpg
Min. 1 = 22.57 ± .01 mpg
Min. 2 = 22.40 ± .01 mpg

as obtained from the light curve given in figure 1.

The ephemeris is:

$$\text{Min. 1} = \text{JD}\odot\ 2433980.859 + 6^{d}.06702 * E$$

Assuming a distance modulus of 27.8, as given in (1), the blue absolute magnitude should be about:

$$Mb = -6$$

supposing that the two components are practically identical to each other.

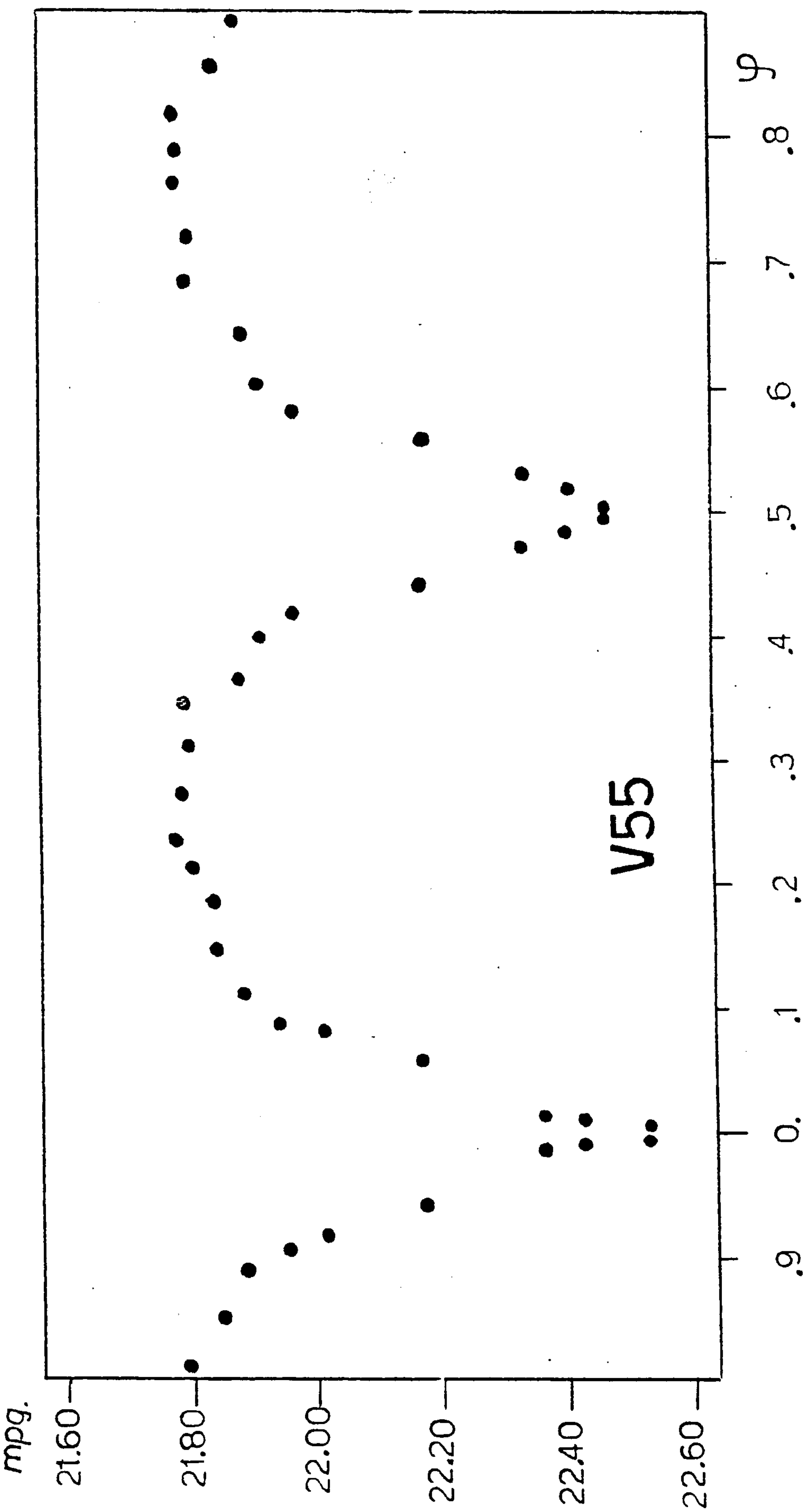

Figure 1: Light curve of V55 in NGC 2403 (normal points).

It follows from this that their spectral type should approximately be O7V. However, as no (B-V) index is available, one can only surmise the approximate spectral type mentioned above.

The photographic light curve is shown in figure 1. It is made of normal points calculated from the observations; they have been folded around the instant of eclipse in the vicinity of the minimum.

The period given in the ephemeris above is only the observed period which fits best the observational data.

It is obvious that the value given above is not the orbital period of the system as the radial velocity of the galaxy which contains the star has an influence.

In point of fact, assuming the radial velocity of NGC 2403 to be approximately (1):

$$RV = (210 \pm 33) \text{ Km/sec}$$

the sideral orbital period of V55 is:

$$P_o = P_{obs}\left[1 + RV/c\right]^{-1}$$

that is to say:

$$Po = 6^d.0628 \pm 0^d.0007$$

or roughly 6 minutes less than the observed period.

3: SOLUTION OF THE LIGHT CURVE

The solution of the light curve was obtained in the frequency domain by means of a polynomial analysis, assuming that the two components were distorted polytropes with an index n=5 (corresponding to the Roche model)(2).

The variation of luminosity out of eclipse underwent a harmonic analysis using the following function:

$$\tilde{m}(\theta) = \sum_{i=0}^{i=4} c_i \cos^i \theta \qquad (1)$$

The three $\mathfrak{A}_j$ integrals (j=1,2,3) required for the solution were obtained by a numerical integration, using:

$$\mathfrak{A}_j = \beta_j \left[1 - \ell_o^*\right]^{-1} \int_{\ell_{oj}}^{\ell_{jB}} \sin^2\theta(\ell^*)\, d\ell^* \qquad (2)$$

where

$$\ell^* = 2.512^{\,m - \tilde{m}(\theta)} \qquad (3)$$

and l^*_{ja}, l^*_{jb} are the suitable limits of the integration interval, summarized in table 1, together with the β_j coefficients.

Table 1 : limits of the integration interval

j	l^*_{ja}	l^*_{jb}	β_j
1	$(3+l^*_o)/4$	$(1+l^*_o)/2$	4
2	$(9+11*l^*_o)/20$	$(1+3*l^*_o)/4$	5
3	$(1+4*l^*_o)/5$	$(1+19*l^*_o)/20$	20/3

This procedure, applied to the two minima, yielded two separate solutions. On examining the values of the spherical orbital elements obtained from the two minima, discrepancies could be noticed, except for the fractional radius of the smaller component and for the luminosity.

The best solution predicts that the primary minimum occurs when the smaller star, which is also the fainter, eclipses the other (transit).

The value of the limb-darkening coefficient was assumed from the tables of AL NAIMIY (3), considering the spectral type (O7V) and also the fact that the photographic material and the techniques used by TAMMAN and SANDAGE (1) made it possible to set the equivalent wavelength of observation at λ_{eq} = 4250 Å.

The orbit of V55 was assumed to be circular, although the discrepancies noted in the orbital elements for the two minima could be eliminated by supposing an elliptical orbit. On the other hand, the light curve does not show any shift of the position of the secondary minimum around φ =0.5 Merging the solution obtained separately for the two minima, a satisfactory solution was reached for the whole light curve.

This was done by taking in consideration the effective shape of the two components of the system.

The results are shown in Table 2 below.

Table 2 : Photometric orbital elements

primary component	secondary component
a_1 = .387 ± .001	a_2 = .320 ± .001
b_1 = .358 ± .001	b_2 = .303 ± .001
c_1 = .341 ± .001	c_2 = .294 ± .001
d_1 = .376 ± .001	d_2 = .314 ± .001
i = 87°.1 ± 0°.5	
L_1 = .59 ± .01	L_2 = .41 ± .01
u_1 = .27 (assumed)	u_2 = .27 (assumed)
Min. 1 = transit	

The elements summarized in Table 2 give a theoretical light curve which has been plotted over the observational data in figure 2.

The agreement is optimal, and therefore the orbital solution described in Table 2 must be considered satisfactory.

4: DISCUSSION

The analysis of the light curve has shown that the V55 system is composed of two stars, the main component being brighter and hotter.

This, together with the fractional dimensions of the components, suggests a detached system.

This structure is shown in figure 3, where the dotted curved line represents the Roche lobes for a value of q=m2/m1 equal to:

$$q = .92 \pm .01$$

This value of the mass ratio is the one which gives the best agreement between the observed light curve and the computed orbital elements.

Unfortunately, the uncertainty on the spectral type has an incidence on the correct determination of the temperature of the two stars composing the eclipsing system.

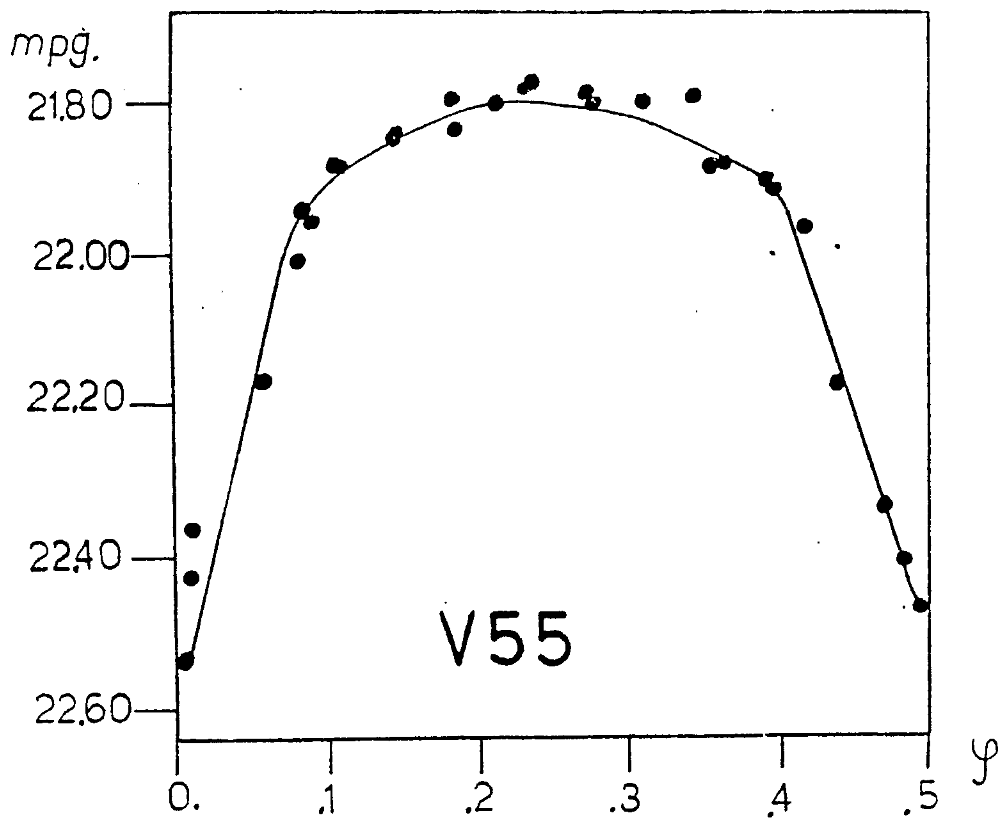

Figure 2: Theoretical light curve plotted over the normal points. These have been folded around the instant of eclipse as a reflecting axis in the vicinity of φ =0.5

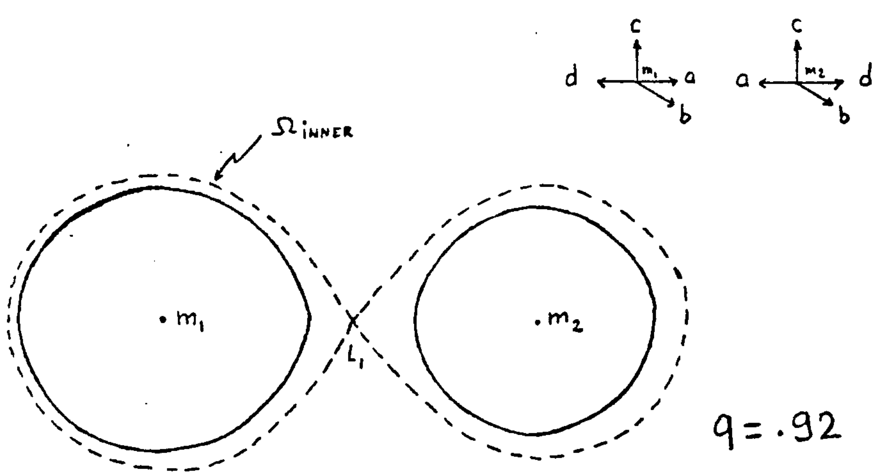

Figure 3: Structure of the binary system V55 in NGC 2403. The plain curved line shows the shape of the components, while the dotted curved line shows the inner equipotential surface (Ωinn).

The assumption that the hotter star has a temperature of about 35000 °K leads to a temperature of 34700 °K for the secondary, supposing that the two stars do radiate as black bodies.

In any case, such values result in an optimal agreement with the model assumed.

5: CONCLUSION

The present paper has discussed the light curve of the system V55 in galaxy NGC 2403 of the M81 group.

Although this system appears to be the most distant eclipsing variable known so far, the light curve yields fairly good orbital elements.

The analysis of other systems in neighbouring galaxies will be the subjects of papers to follow.

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