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PHOTOMETRY OF SS 433 OVER 7 YEARS: STUDY OF TWO PERIODICITIES

TSEVI MAZEH[1]
Harvard-Smithsonian Center for Astrophysics
JAMES C. KEMP
Department of Physics, University of Oregon
AND
ELIA M. LEIBOWITZ, HERBERT MENINGHER, AND HAIM MENDELSON
The Wise Observatory, Tel Aviv University
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ABSTRACT

The photometric data of SS 433 which now extend over seven years (Kemp *et al.* 1986) are multifrequency analyzed. The analysis shows the long-known interdependence between the two periodicities of 13 and 162 days, associated with the frequencies f_{162} and f_{13} and their harmonics. In addition, we detected unambiguously the $2f_{13}+f_{162}$ frequency as the strongest beat periodicity, with an amplitude of 0.083 ± 0.014 mag. The $2f_{13}+2f_{162}$ frequency, which was expected to be the frequency of the mass transfer rate modulation, was only marginally detected. Our finding can be interpreted in the framework of the nodding model of a precessing object.

Subject headings: photometry — stars: individual (SS 433)

I. INTRODUCTION

In an earlier paper (Kemp *et al.* 1986, hereafter Paper I) the data obtained by seven years of photometry of SS 433 have been presented. The data show clearly two very prominent periodicities at periods of 162 and 13 days. These two periodicities, found originally by the extensive spectroscopic study of the star, reflect the precession of the relativistic jets (see Margon 1984) and the orbital motion of the binary system (Crampton and Hutchings 1981). The photometric periods and phases agree very well with the spectroscopic ones (Paper I).

Previous analyses of the accumulating photometric data have shown that the two periodicities are interdependent (Gladyshev 1981; Cherepashchuk 1981; Leibowitz, Mazeh and Mendelson 1984; Goncharskii, Metlitskaya and Cherepashchuk 1984; Leibowitz *et al.* 1984; Paper I). The binary light curve is very different at various phases of the 162 day precession cycle and vice versa. The dependence of each photometric periodicity on the phase of the other one is further complicated by the possible existence of *other* periodic photometric modulations. Indeed, several studies have suggested the presence of various beat frequencies of the precessional and the orbital frequencies or their harmonics in the photometric data of SS 433 (Mazeh, Leibowitz, and Lahav 1981; Leibowitz 1984), as well as in the recorded X-ray and radio intensity of the system (Band and Grindlay 1984). The extensive databank of Paper I and its relatively long time baseline make it possible now to further study these possible additional frequencies.

The potential importance of studying *all* the frequencies of the system has been noted already by Katz (1981). He has pointed out that some of the models for the mechanism behind the 162 day precession can be ruled out if the beat frequencies can be identified unambiguously. Indeed, great effort has been dedicated to find the beat periodicities of SS 433 in the spectroscopic data of the relativistic jets, by detailed analysis of the "moving lines" (Newsom and Collins 1980, 1981, 1982; Margon, Grandi, and Downes 1980; Katz *et al.* 1982; Mammano *et al.* 1983; Collins and Newsom 1986). In this work we try to find the corresponding photometric periodicities (Matese and Whitmire 1982) by detailed periodic study of the data base of Paper I. We further apply a two-dimensional Fourier analysis to the observational results. A similar analysis has been applied very effectively to the photometric data of HZ Her (Deeter *et al.* 1976), another case where a pair of prominent periodicities and a number of beat frequencies were observed, and a precessing disk model has been proposed. The results are interpreted in the framework of the theory for the nodding motion of a precessing disk (Matese and Whitmire 1982; Katz *et al.* 1982; Collins 1985; Collins and Newsom 1986).

II. ONE-DIMENSIONAL FOURIER ANALYSIS

The data of Paper I will be used throughout this study, except for the last 10 points and the two most extreme measurements. The latter, if real, are probably due to some rare events and probably do not represent the periodic variation of SS 433. The last 10 points were included in our files too late to be analyzed. The power spectrum of the accumulated data is reproduced in Figure 1 (see Paper I). The spectrum is dominated by high-power components around three frequencies: f_{162}, f_{13}, and $f_{6.5}$. Their best values are

$$f_{162} = 0.00615 \pm 0.00015 \text{ day}^{-1} ,$$
$$f_{13} = 0.07655 \pm 0.00020 \text{ day}^{-1} ,$$
$$f_{6.5} = 0.15287 \pm 0.00020 \text{ day}^{-1} .$$

The errors are the central peaks' HWHM. The frequencies correspond to the periods of 162.5 ± 4 day, 13.06 ± 0.03 day, and 6.54 ± 0.01 day, respectively. Clearly, $f_{6.5}$ is the first harmonic of f_{13}. Therefore it will be alternatively referred to as $2f_{13}$. For the exact value of f_{13} we will use a frequency of 0.07645 day^{-1} (see Paper I).

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[1] On leave from The School of Physics and Astronomy, Tel Aviv University.

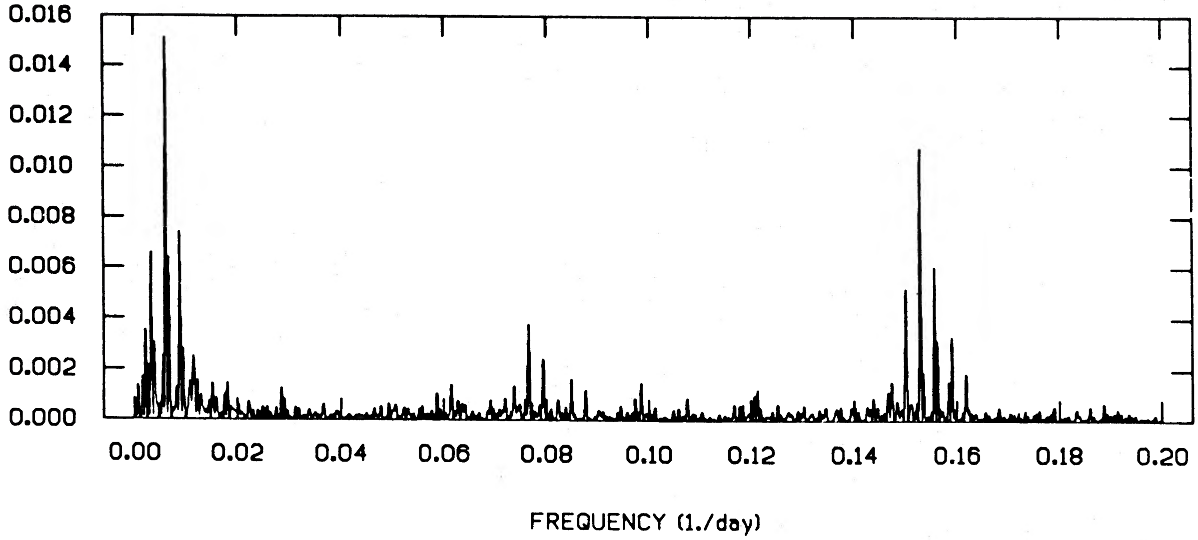

FIG. 1.—Power spectrum, in arbitrary units, of the *V*-band measurements of SS 433 (*see* Paper I)

Figure 2*a* presents three enlarged sections of Figure 1 around f_{162}, f_{13}, and $2f_{13}$. It is clear from the figure that each of these three dominant frequencies is accompanied by a side lobe on each side of the main peak. The "blue" (higher frequency) and the "red" lobes are noted in the figure by $+\Delta$ and $-\Delta$, respectively. The average separation between the side and the main lobes is

$$\Delta = 0.00277 \pm 0.00007 \text{ day}^{-1} .$$

This frequency corresponds to a period of 361 ± 9 day and is obviously due to the structure of our window function. The side lobes reflect annual gaps in the data, present because SS 433 could not be observed during the winter time (Mazeh, Leibowitz, and Lahav 1981; Paper I).

Figure 2*a* reveals another small peak at a frequency of

$$f_3 = 0.15905 \pm 0.00020 \text{ day}^{-1} .$$

As noted in Figure 2*a*, this peak has similar sidelobes on both sides. The f_3 periodic modulation clearly represents a beat phenomenon of f_{162} with f_{13}, since it fulfills the equation

$$f_3 = f_{162} + 2f_{13}$$

with a very good accuracy.

This periodic modulation is *real* and is not an observational artifact outcome of the f_{162}, f_{13}, and $2f_{13}$ frequencies. To prove this statement we performed two one-dimensional Fourier analysis tests:

1. We subtract from the data a sum of sine and cosine functions with the f_{162} and f_{13} frequencies and their first harmonics. The individual coefficients of the different sine and cosine functions were found *simultaneously* by a least-square procedure. Three sections of the power spectrum of the *residuals* are plotted in Figure 2*b*. The figure clearly shows no hint for f_{162},

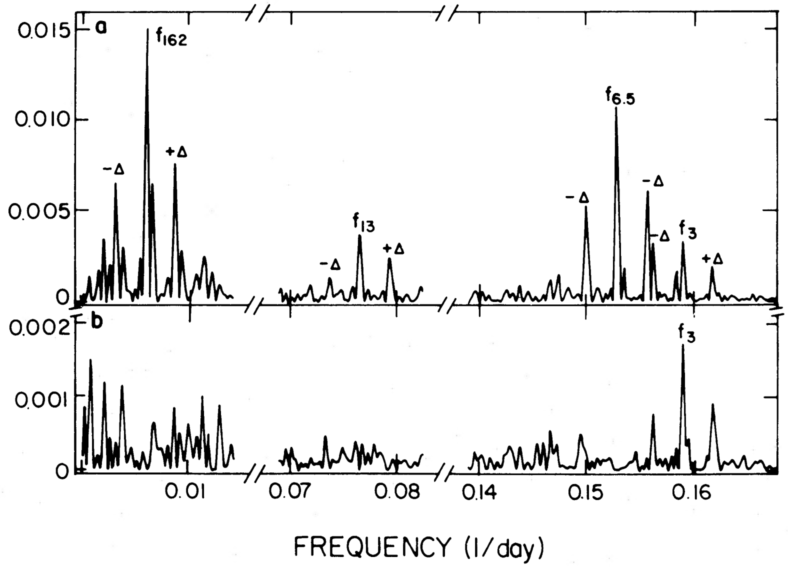

FIG. 2.—(*a*) Three enlarged section of the power spectrum of the real data. The same units as in Fig. 1. The $+\Delta$ and the $-\Delta$ denote the "blue" and the "red" annual sidelobes of each frequency, respectively. (*b*) The same as (*a*) for the residuals, after the f_{13} and f_{162} frequencies and their harmonics were subtracted (*see text*). Units same as in Fig. 1.

f_{13}, or $2f_{13}$ but still shows f_3 together with its sidelobes as the highest peak. (Note the different scale in Figs. 2*a*–2*b*.)

2. We generated artificial data from the sum of the periodic functions which were subtracted from the real data to produce Figure 2*b*, using the real observational timings. We then Fourier analyzed the simulated data. This was done to check if pure periodic modulations with frequencies of f_{162} and f_{13} and their first harmonics alone can produce a power spectrum with a peak at f_3, as was really observed. The power spectrum of the simulated data showed peaks at f_{162}, $2f_{162}$, f_{13}, and $2f_{13}$, and the corresponding side lobes. *No peak at* f_3 *could be traced* at the simulated power spectrum.

We therefore conclude that the f_3 modulation is *real* and is not due to the observational window function and some of the other frequencies.

As can be noted from Figure 2*a*, the high resolution of the power spectrum, due to the long base time of the present accumulated data bank, resolves for the first time the difference between $2f_{13} + \Delta$ and $f_3 - \Delta$. In the previous studies (Mazeh, Leibowitz, and Lahav 1981; Leibowitz *et al.* 1984) the resolution between the two was not possible. Therefore, the peak at $2f_{13} + \Delta$ ($\approx f_3 - \Delta$), which corresponds to a period of $\sim$6.43 day, has been mistakenly considered to be a real one and to represent some beat phenomenon. The present power spectrum clearly shows that this is not the case, and the *real* beat periodicity is f_3 ($= f_{162} + 2f_{13}$).

Figures 1 and 2 also show that the beat frequency appears on the "blue" side of $f_{6.5}$. No beat frequency with the *same intensity* can be found on the "red" side of $f_{6.5}$. This feature was noted by previous photometric studies of SS 433 (Mazeh, Leibowitz, and Lahav 1981; Leibowitz *et al.* 1984).

III. TWO-DIMENSIONAL FOURIER ANALYSIS

The periodic optical behavior of SS 433 can be presented as a two-variable function, where the two variables are the phases of the orbital and the precessional cycles. As noted by Deeter *et al.* (1976), a natural orthogonal set of functions that span the space of all possible periodic functions of the two variables is the sine and cosine functions of the sum and differences of harmonics of f_{13} and f_{162}. Following their prescription, we applied the standard regression method to fit the SS 433 data to the general sum of the periodic functions of the mixed harmonics.

The set of functions we used to fit the data include:

1. Nonmixed terms of sine and cosine functions with the f_{13} and the f_{162} frequencies and their harmonics:

$$\sin/\cos\ [k2\pi f_{13}(t - t_0)]\ , \quad k = 1, 2, 3, 4$$

and

$$\sin/\cos\ [k2\pi f_{162}(t - t_0)]\ , \quad k = 1, 2, 3, 4\ .$$

2. Mixed terms of the two harmonics:

$$\sin/\cos\ [2\pi(nf_{13} + mf_{162})(t - t_0)]\ ,$$

$$n = 1, 2, 3, 4\ , \quad m = \pm 1, \pm 2, \pm 3, \pm 4\ .$$

TABLE 1

THE NONMIXED TERMS

	−2.856	
V_0	sin	cos
f_{13}:	0.024	−0.127
$2f_{13}$:	−0.023	−0.177
$3f_{13}$:	0.002	−0.037
$4f_{13}$:	0.026	−0.037
f_{162}:	−0.125	−0.214
$2f_{162}$:	0.025	0.038
$3f_{162}$:	−0.014	−0.006
$4f_{162}$:	−0.013	−0.003

Together with the constant term we have 81 coefficients to fit.

The results, using JD 2,440,003.43 as t_0 (Paper I), are given in Table 1 (nonmixed terms) and Table 2 (mixed terms). Results are given in magnitudes. The estimated 1 σ error is $\sim$0.014 mag for all coefficients.

The coefficients found were used to construct a two-dimensional isophote map depicted in Figure 3, following the work of Deeter *et al.* (1976) on HZ Her and the analysis of the infrared data of SS 433 by Kodaira, Nakada, and Backman (1985). The figure presents the best-fit *periodic* variation of SS 433, and indeed the two prominent periodicities are easily noticed. Even the interdependence of the two modulations can be followed. For example, the binary variation is most pronounced between precessional phases 0.4 and 0.6, and it has a completely different shape at precessional phase, say, 0.0. The precessional variation has a secondary maximum at a binary phase 0.2–0.5, a feature which does not appear at other binary phases.

Deeter *et al.* (1976) pointed out that the fit of the data to the sum of mixed harmonics can help to distinguish between sidelobe peaks and real beat frequencies. Table 2 indicates, indeed, that some beat frequencies are present in the data. The *largest* amplitude, 0.083 mag, is found with the $f_3(= 2f_{13} + f_{162})$ fre-

TABLE 2

THE MIXED TERMS

	f_{13}		$2f_{13}$		$3f_{13}$		$4f_{13}$	
FREQUENCY	sin	cos	sin	cos	sin	cos	sin	cos
f_{162}:	−0.007	−0.016	0.013	0.082	−0.008	0.009	0.023	0.002
$-f_{162}$:	0.016	0.018	−0.036	−0.030	−0.016	0.020	0.004	0.012
$+2f_{162}$:	−0.019	−0.009	0.005	0.024	−0.009	−0.032	0.027	−0.005
$-2f_{162}$:	0.068	0.017	0.011	−0.008	0.011	0.015	0.014	0.007
$+3f_{162}$:	−0.010	−0.010	−0.001	0.013	0.007	−0.002	0.022	−0.009
$-3f_{162}$:	−0.008	0.024	0.023	0.027	−0.011	−0.012	0.002	−0.005
$+4f_{162}$:	−0.011	0.018	0.022	−0.001	0.022	−0.025	−0.007	−0.018
$-4f_{162}$:	−0.023	−0.002	−0.004	0.015	−0.015	−0.020	−0.002	−0.004

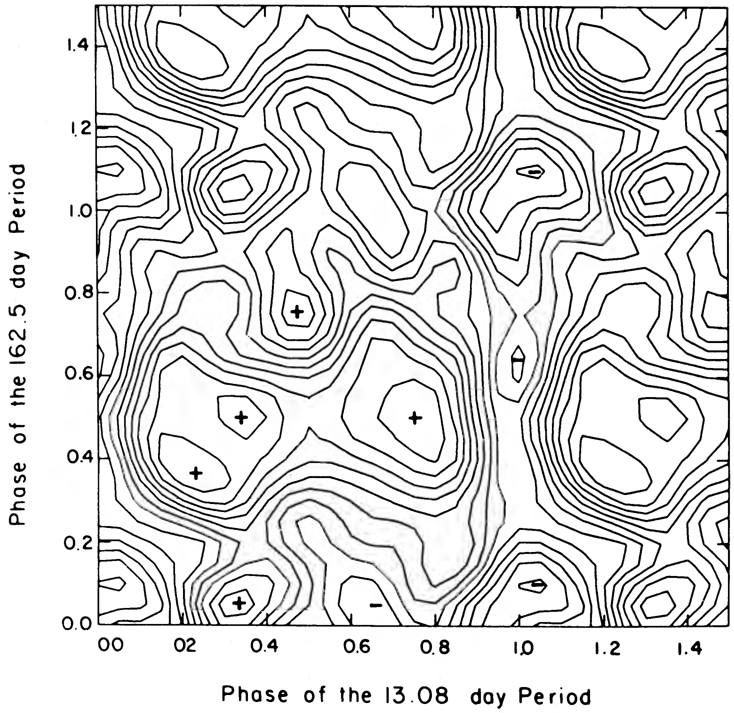

FIG. 3.—An isophote map of the SS 433 periodic modulation as a function of the phases of the two cycles (*see text*). Pluses denote local maxima, minuses denote minima.

quency, in complete agreement with § II. The second largest amplitude, 0.070 mag, was found with the $f_{13} - 2f_{162}$ periodicity. The uncertainty for all the amplitudes is again 0.014 mag. Only two other periodic modulations where found with significance greater than 2 σ. These are associated with the frequencies $2f_{13} - f_{162}$ and $2f_{13} - 3f_{162}$, with amplitudes of 0.047 and 0.035 mag, respectively. The $2f_{13} + 2f_{162}$ periodicity had an amplitude of $\sim$0.024 mag.

IV. DISCUSSION

Our Fourier analysis shows clearly that the strongest *beat* frequency that can be followed by the photometric data of SS 433 is the $f_3(=2f_{13} + f_{162})$ frequency. We further show that other beat frequencies with periods of $\sim$6 days, like $2f_{13} + 2f_{162}$, $2f_{13} + 3f_{162}$, or $2f_{13} + 4f_{162}$, are much weaker. The results also indicate that the power at the "red" side of the $f_{6.5}$ peak is much weaker than the power of f_3 and its neighbors.

These findings are consistent with the precessing disk model. In this picture SS 433 consists of a mass transfering system which includes a compact object and an accretion disk around it. The relativistic jets are ejected perpendicular to the disk which precesses around the total angular momentum vector of the system. The slaved disk model (Shakura 1973; Roberts 1974) has been proposed as the mechanism behind the precession (Katz 1980; Whitmire and Matese 1980; van den Heuvel, Ostriker, and Petterson 1980; Hut and van den Heuvel 1981). According to this model the disk precession is slaved to the driven precession of the companion optical star, which has a rotation axis that is tilted with respect to the binary orbital plane.

What kind of beat frequencies would we expect in the framework of this model? Katz (1981) noted that the driven precession is in the direction opposite to that of the binary motion. Therefore the compact object moves relative to any feature of the optical star in a frequency of $f_{13} + f_{162}$. Physical processes which depend on the relative position of the two stars are thus expected to be modulated with this frequency or its harmonics. The mass transfer rate, for example, is supposed to vary with the first harmonic of this frequency—$2f_{13} + 2f_{162}$ (Matese and Whitmire 1982), because of the Avni and Schiller (1982) effect. It was, indeed, proposed that the expected variation of the mass transfer rate modulates the optical intensity of SS 433 (Leibowitz 1984, hot spot) and the radio and X-ray output of the system (Band and Grindlay 1984, radio and X-ray flares). However, the present study shows that such a modulation can not be found in the photometric data above the noise level. The 1 σ upper limit is $\sim$0.04 mag.

Our findings are surprisingly similar to the results of Katz *et al.* (1982), who analyzed the radial velocity measurements of the moving lines. They also have found that when the averaged 162 day periodicity is subtracted from the data, the highest peak in the power spectrum of the residuals is that of f_3. They have interpreted their results as the effect of precessing and nodding disk. They have shown that the precessing disk is expected to perform a nodding motion with the frequency of $2f_{13} + 2f_{162}$, driven by the gravitational torque of the optical star. They have further showed that the inclination angle of the nodding disk, relative to a fixed axis in space, is modulated mainly with the frequency $2f_{13} + f_{162}$. Their calculations predict that the amplitude at this frequency would be larger by a factor of 10 than the amplitude at any other beat frequency. Similar results have been obtained by the theoretical work of Matese and Whitmire (1982), who have considered the nutation of the optical star and its impact on a slaved disk, and by Collins (1985) and Collins and Newsom (1986) who have studied the general case of nutation of any spinning object in the system.

The nodding model interprets radial velocity measurements of the jets as an outcome of an inclination variation alone, since the speed of the jets is assumed to be constant. This interpretation is in agreement with our finding, if we assume that the photometric intensity of SS 433 *also* depends on the jet inclination with respect to our line of sight. This is a very natural assumption, since the jets are perpendicular to the disk in the precessing disk model. The 162 day photometric cycle of SS 433 has been interpreted, indeed, as an outcome of the varying aspect of a precessing disk (Mazeh, Leibowitz, and Lahav 1981; Anderson, Margon, and Grandi 1983; Paper I). Therefore, if we assume that the disk brightness is a function of its inclination, we can then interpret the 6.28 day periodic modulation (frequency of $2f_{13} + f_{162}$) as due to the nodding motion. The nodding model would also apply to the small amplitude, if any, of the 6.06 and 5.83 day periodicities in the photometric data.

The ratio of the amplitudes of the f_{162} and the $2f_{13} + f_{162}$ frequencies was found by Katz *et al.* to be 0.076. The photometric ratio found here is much larger—0.33 ± 0.06. This also can be accounted for in the framework of the nodding theory. In the Katz *et al.* model, the nodding of the inner part of the disk, which they assume determines the orientation of the jets, is slaved to the motion of the outer rings, where the nodding is generated (Katz *et al.* 1982; Margon 1985). This is the case because the driving torques exerted by the optical star are significant only for disk rings with large radii. This model implies that the amplitude of the nodding motion of the outer part of the disk might be substantially larger than that of the jets. Since the photometric output of the disk is produced at its outer part, we can expect a larger relative amplitude for the $2f_{13} + f_{162}$ frequency in the photometric data. The photometric amplitude depends also on the structure and shape of the outer edge of the disk. To study this dependence one needs to construct a detailed model of the disk, which is beyond the scope of this work. The same argument applies to the models in which the nodding motion is generated at the optical star (Matese and Whitmire 1982; Collins 1985; Collins and Newsom 1986). These models also include an assumption about the migration of the nodding motion from the outer part of the precessing disk (which is slaved to the motion of the optical star) into its most inner rings.

The assumption about the migration of the nodding motion does not account only for an amplitude difference between the photometric f_3 periodicity and the radial velocity one, but also predicts a phase delay between the two modulations. This is indeed the case. From the results of Table 2 we find that the intensity maxima of the f_3 photometric cycle occur at

$$\mathrm{JD}\ 2{,}440{,}003.6(\pm 0.17) + 6.2874n\ .$$

One of these timings is JD 2,443,549.7 ± 0.17. From Katz *et al.* (1982) results we derive an epoch of JD 2,443,550.7 ± 0.06 for the maximum of the f_3 radial velocity modulation. These values imply that the photometric maxima appear about a day before the radial velocity ones, in remarkable agreement with the nodding model.

The large amplitude of the beat *photometric* frequency might also be caused by the specific dependence of the system apparent brightness on the disk inclination, which can be very different from the dependence of the radial velocity of the jets. While the radial velocity depends linearily on the cosine of the disk inclination, the system brightness can have a nonlinear dependence (Leibowitz 1984), along with some other light sources in the system. Moreover, the eclipses that the different components undergo with the $2f_{13}$ and f_{162} frequencies (Mazeh, Leibowitz, and Lahav 1981; Henson *et al.* 1983; Leibowitz 1984; Paper I) can introduce *several* beat frequencies into the photometric data. This effect can also contribute to the extra power at the $2f_{13} + f_{162}$ modulation and can account for the presence of the $2f_{13} - f_{162}$, $2f_{13} - 3f_{162}$, and $f_{13} - 2f_{162}$ periodicities.

The nodding interpretation of the f_3 modulation is by no means the only possible one. For example, this periodicity could arise from the interdependence of the f_{13} and f_{162} modulations. However, such an interpretation is very unlikely, because (1) we do not find similar amplitudes for frequencies which are on the other side of $2f_{13}$, and (2) the f_3 modulation is found in the radial velocity data, where no f_{13} or $2f_{13}$ periodicities are known to exist.

We conclude, therefore, that the existence of the "blue" beat frequency, found both in the spectroscopy of the jets and in the optical intensity of SS 433, is consistent with the nodding model of the precessing disk. The appearance of other weak periodicities in the photometric data, as well in the spectroscopic power spectrum, is still to be understood. To explain fully this complicated system, a detailed physical photometric model which uses the present results of the multifrequency analysis has to be constructed.

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JAMES C. KEMP: Department of Physics, University of Oregon, Eugene, OR 97403-1274

ELIA M. LEIBOWITZ, TSEVI MAZEH, HAIM MENDELSON, and HERBERT MENINGHER: The Wise Observatory, Tel Aviv University, Ramat Aviv, Israel