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SS 433: INTENSIVE 4 MONTH LIGHT CURVES

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ABSTRACT

Photometry covering 100 nights during 1979 July–November is reported; in an unfiltered band (effectively 5200–8000 Å), in a V band; in a far-red band; and with a few measures in B. We find (1) correlation with the 13 day period of Crampton, Cowley, and Hutchings, in the form of a double-peaked light curve; and (2) a more tentative connection with the 164 day "precession" period (Margon *et al.*), suggested by a broad light minimum near a critical phase in the long cycle.

Subject headings: stars: binaries — stars: emission-line

I. BACKGROUND

A variety of optical, radio, and X-ray investigations have been carried out on the unusual object SS 433, as summarized in late 1979 by Overbye (1979). Two periodicities in the object are recognized: (1) the 164 day "precession" period (Margon *et al.* 1979), and (2) a close binary-like period (~13 days) seen in the radial-velocity variations of the so-called stationary lines (Crampton, Cowley, and Hutchings 1980, hereafter CCH).

Photometry of SS 433 has not been reported as rapidly and systematically as the spectroscopy. This might have had to do with the suspicion that the unusual spectral behavior, particularly the widely moving emission lines, would be expected to produce spurious or complex photometric effects in the standard color bands (*UBV*, etc.).

At Pine Mountain Observatory we elected to begin a photometric program in very broad-band, unfiltered light, hoping thereby to avoid significant spurious variations due to shifts of the moving emission lines. The program, however, also included a V band and some measures in a special far-red band. Collaborative observations in V and B bands were undertaken by two of us (E. M. L. and T. M.) at Wise Observatory.

Our combined observations described here make up one of only about three extensive, homogeneous sets of contemporary photometric data on SS 433, as far as we are aware. The other sets of data are by Gladyshev *et al.* (1979) and Giles *et al.* (1980).

An initial announcement was made by Kemp, Barbour, and Arbabi (1979) of the finding of a light variation, probably related to the "binary" period of CCH, in the form of a double-peaked light curve with apparent half-period close to 6.5 days. The reader will see from our report below, and from reports by the other groups just referred to, that the photometric variations in SS 433 are far from simple, involving, no doubt, stochastic effects as well as interactions between the long "precession" process and the orbital motion, the latter having a fairly definite period in the range 12–13 days.

II. OBSERVATIONS

The photometry at Pine Mountain Observatory (PMO) and Wise Observatory (WO) was referenced against a main comparison star which we call star 1, located 1'.6 NNW of SS 433. It is the northern bright star of the diamond-shaped small constellation in the field. At PMO we studied some 10 field stars and selected, besides star 1, also a seemingly invariant check star designated star a, located 5'.6 ENE of star 1. For star 1 we estimate $V = 11.2$, $B - V \approx +1.7$; it seems to be a late M star, as per a spectrum by Margon (1979). For star a, $V = 10.8$ and $B - V \approx +0.3$. Thirty measures during 1979 July–November showed no relative variation between stars 1 and a exceeding 0.05 mag. Allowing for any measuring errors we conclude that no real variation as large as 0.07 mag, peak-to-peak, occurred in stars 1 and a on any time scale ranging from a day to 4 months. Star 1 is a fairly good color match for SS 433, which has a $B - V$ of about $+2.1$.

Our most extensive data set is that obtained at PMO in an unfiltered-light band with S-20 response. Tests with a series of filters, assisted by spectra sent to us by B. Margon, enabled us to estimate the expected energy-weighted pass band in observations of SS 433, using the unfiltered S-20 band. The effective half-energy wavelengths appeared to be about 5200 and 8000 Å. *Motions* of the moving Hα lines across this band (see Margon *et al.* 1979) would not be expected to produce a spurious photometric variation as large as 0.1 mag, which is less than a fifth of the scale of variation observed (see Fig. 1). Furthermore, most of the line motion is on the 160 day time scale, and false photometric effects on 6 or 13 day time scales would seem to be quite negligible. Of course, the unfiltered band cannot discriminate between flux changes in the continuum and line-intensity changes, although we estimate the relative contributions in a concluding section.

A long series of photometric or partly photometric nights occurred at Pine Mountain in summer and early fall 1979, resulting in the almost unbroken record in the S-20 band seen in Figure 1. On partly cloudy nights it was possible to obtain accurate measures in brief

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clear periods, 15–30 minutes in duration, due to the high photon-collection rate in unfiltered light.

Telescopes of apertures 81 cm and 1.02 m were used at PMO and WO, respectively. The telescope at PMO was used in a computer-controlled, semi-automatic photometry mode (see Kemp *et al.* 1979). An aperture of 9″ diameter was used. Because of the complex sky-brightness pattern around SS 433, we were careful to sample the sky repeatedly at a single selected position, namely, a position due west of SS 433 and due south of star 1. Repeated, timed, object-sky-comparison sequences were carried out, composed of individual 50 s integrations, and errors were computed from the results from such sequences. Coverage of SS 433 ranged from 6 hours on some nights to as short as 20 minutes on a couple of nights.

Real-time plots of the bulk of our data are given in Figure 1. The data include (1) 99 nights of observations in unfiltered S-20 light, at PMO; (2) 65 measures in the *V* band, the sum of 12 at WO and 53 at PMO; (3) 11 measures in the *B* band at WO, taken during July–October; (4) 26 measures at PMO, during September 7–November 8, in a special far-red band. This band was defined by a Corning 2-64 cut-on filter combined with the S-20 response, and is effectively centered at 7300 Å with a FWHM of roughly 1100 Å. (The band is redward of "stationary" Hα, but it includes the moving $H\alpha^+$ line.)

With only a few exceptions the measuring errors in the unfiltered, *V*, and far-red bands did not exceed 0.06 mag, and in most cases were smaller. Thus virtually all of the structure seen in Figure 1 is real.

Brief mention should be made of some polarimetry, also carried out at PMO, on 33 nights during 1979 June–November. This was in unfiltered S-20 light. These measurements were not accurate enough to answer the question of variable polarization in SS 433. However, we found an overall average polarization of 3.0 ± 0.5% with position angle about 10° (see also Kemp 1979). Upper limits for Fourier amplitudes of variation in either Stokes parameter are given as 0.7%, for specific periods of 6.5 and 13 days.

III. RESULTS

In the real-time plots of the light variation in the S-20 and *V* bands (Fig 1), we see the following features:

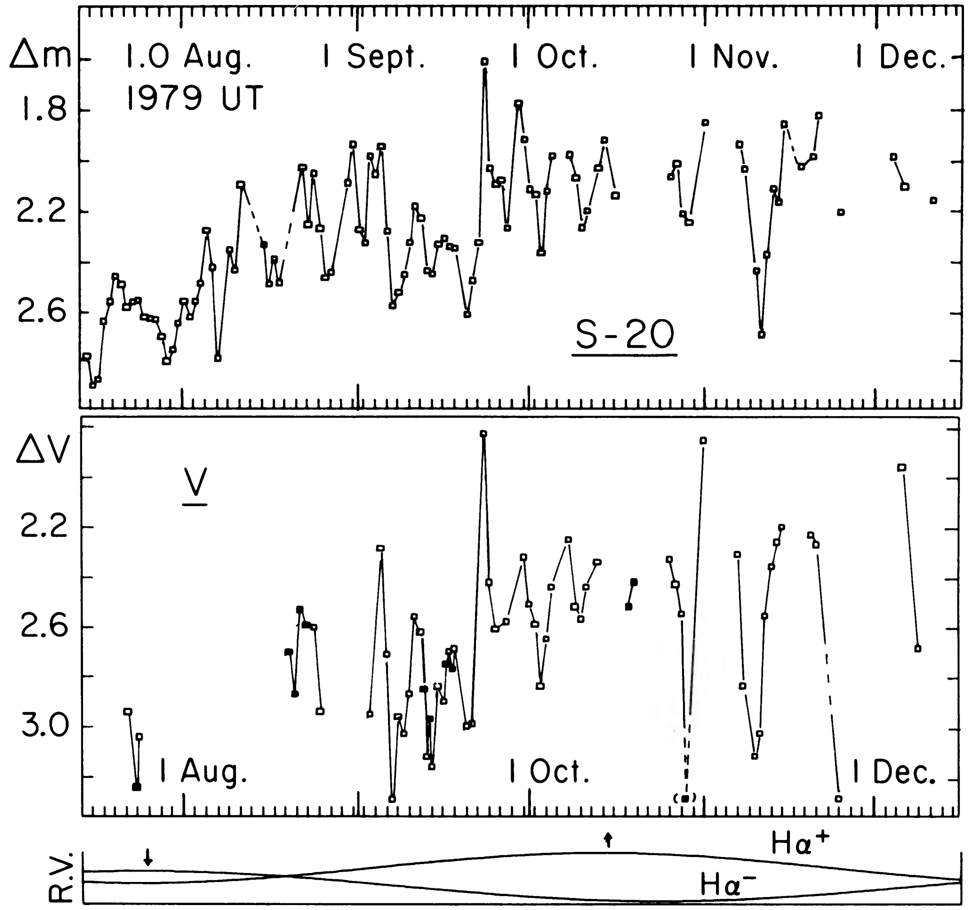

FIG. 1.—Nightly photometric means, 1979 July through early December, SS 433. The upper panel shows unfiltered-light data, all at the 81 cm telescope at Pine Mountain, Oregon. The middle panel is *V* band: PMO points are open boxes, WO points taken with the 1.02 m telescope are filled boxes. Magnitudes are relative to star 1 (see text). Connecting lines are merely for visual aid in following the variations. The bottom panel is an idealization of the Margon *et al.* (1979) radial-velocity curves of the moving Balmer lines.

1. A long-term brightness rise, from a minimum in mid-July to a very broad maximum, or leveling off, in October–November. This long-term change is clearest in the unfiltered band.

2. Relatively rapid variations on a time scale of 1 to 10 days. There is an obvious suggestion of some sort of period or quasi period in this time domain, although the amplitude would seem to be variable and one sees outburst-like events.

We have analyzed the day-to-day variability by a power-spectrum method, with results shown in Figure 2. For this purpose, the long-term effects have been removed by a low-frequency prewhitening, by subtracting a fitted polynomial $A + Bt + Ct^2$ from the data points. The low-frequency suppression is essential for the S-20 band, in which the slow variation is relatively strong; the suppression has almost no effect on the V band power spectrum. The power spectra were computed by linear regression onto sinusoids at discrete periods (frequencies).

The strongest peak in the power spectra is at essentially 6.45 days. To within errors permitted by the finite time span of the data strings, this period is sensibly one-half of the spectroscopic period of CCH, i.e., half of 13 days.

Possible 1 day aliases of a 13 day or 6.5 day period were considered. We approached this question first by analyzing the data from about 50 of the nights at PMO, having long records spanning more than 4 hours per night. If the variations are approximated as sinusoidal, one can predict the pattern and amplitudes of slopes, dm/dt, expected over sampling times of ~4 hours. The coherent pattern of slopes for a one-day alias would be roughly 6 or 13 times stronger than that for 6.5 or 13 day periodicities. From an analysis based on the slope data we found that the probability was less than 0.01 that the observed 6.5 day variation was due, instead, to a 1 day alias. This conclusion was supported by comparing the PMO and WO data in the V filter, which in several instances (see Fig. 1) were on coincident or adjacent dates, but were separated by ~10 hours due to the longitude difference. A possible very small instrumental offset might be allowed for as between the PMO and WO data. However, no evidence is seen for *systematic* oscillations over ~0.5 days. Along with CCH we reject the 1 day alias.

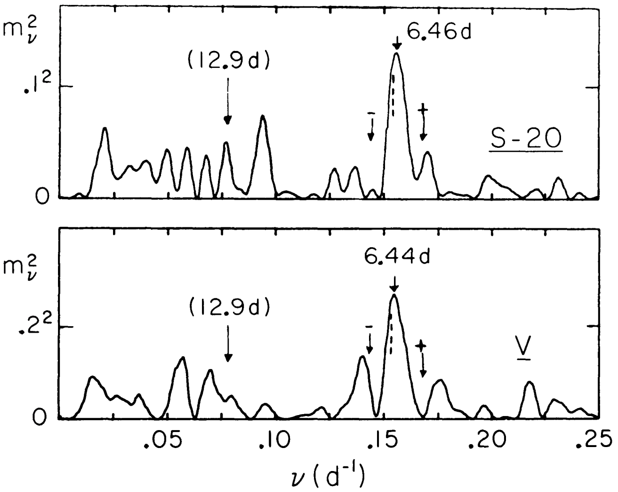

FIG. 2.—Power spectra of SS 433 light variations using data points of Fig. 1. The method is linear regression onto sinusoids, using here 400 discrete frequencies; the shortest period represented is 4.0 days. Long-term variation has been suppressed by removal of terms in the data string proportional to t and t^2. The ordinate here is $m_\nu^2 = C_\nu^2 + S_\nu^2$, where C_ν and S_ν are the cosine and sine Fourier amplitudes.

A periodic or coherent period close to 1 day is ruled out, but several nightly records show fluctuations or slopes several times larger than those expected from the slower variation (period $\gtrsim 6$ days). Such excess hourly variation was noted by Leibowitz, Mazeh, and Sternberg (1979), by Kemp *et al.* (1979), and by Gladyshev *et al.* (1979). As far as we know, such variation is random or flarelike in character. On *very* short time scales (minutes, seconds), SS 433 is quiet (McGraw *et al.* 1979; Beskin *et al.* 1979).

At any power-spectrum period the probability for a random-noise peak is given by $\exp(-x^2/2\sigma^2)$, where x is the observed Fourier amplitude and σ is the rms noise amplitude. The unbiased probability is greater by a factor of the order of the number of independent periods, i.e., by $N/2$, where N is the number of data points. In Figure 2 the 6.45 day peaks have values $x/\sigma = 5.1$ and 4.9 in the S-20 and V bands, respectively; thus the unbiased probabilities for accidental peaks in these cases are each about 0.4×10^{-3}. As for other noticeable peaks in Figure 2, in the S-20 band the second-strongest peak, at $P = 10.8$ days, has an unbiased random probability of about 0.2; in the V band, the peak near $P = 17.5$ days has a probability of 0.4. Thus only the 6.45 day peaks are clearly detectable based on the photometry alone.

In view of the likely connection with a spectroscopic "double" period (i.e., fundamental period) of about 13 days, we show in Figure 3 a folded plot of our data on what we take to be the best-fit "full" binary period, namely, 12.9 days. That is twice our best-fit presumed "half-period" of 6.45 days. Controversy over the most precise full period is discussed later, but we note that the disagreement between our value of 12.9 days and the CCH period of 13.1 days is too small to resolve decisively owing to the limited time scales of the data.

The data as shown in Figure 3 have been treated with low-frequency suppression (polynomial subtraction) as for the power spectra, although this is important only for the S-20 band.

Co-phasing of the CCH radial-velocity curve is hindered by the small period disagreement, coupled with the fact that their data and ours were only partially overlapping in time. Phase 0.0 in Figure 3 corresponds to a central epoch, near the central time of our observations around September 26, of JD 2,444,145.9. The data of CCH on a zero-eccentricity approximation (pure 13.1 day period sinusoidal variation), have a central epoch near the mean time of their observations of JD 2,444,032.11, for maximum positive radial velocity.

Transferring that epoch to our central epoch, if we use the 13.1 day period for the projection, we find that the maximum positive radial velocity in Figure 3 occurs at the position of the *upward solid arrows*: maximum negative velocity occurs at the downward solid arrows. If we project the CCH data ahead, using instead our presumed double period of 12.9 days, we obtain the radial-velocity phasing shown by the dashed arrows in Figure 3.

Lastly, in Figure 4 we show our meager evidence for color variation, on the approximate binary period. The curve of the special index $V - 7300$ refers to V versus the special far-red band mentioned in § II. In neither $B - V$ nor $V - 7300$ does the color variation exceed 0.1 mag; the dashed curves are regressions onto first and second harmonics. The color variation between these bands is not strong.

IV. DISCUSSION

With regard to the 164 day "precession" period, our light curves in Figure 1 show an obvious, but incomplete, connection with this process. Another 1–2 years of data would be needed to check the reproducibility of the long-period pattern. The short-term variations on a time scale of days are comparable in amplitude to the very slow variation; thus a random sampling of points would not define the 164 day light curve. The case for a 164 day light variation in archival photographs (Gottlieb and Liller 1979) seems not to have been well supported by further analysis of such material (Liller 1979). If the pattern suggested in Figure 1 is taken literally, it is inferred that the minimum around July 15 corresponds to a certain phase in the disk-precession cycle (Katz 1980) at which the disk is almost edge-on to the observer.

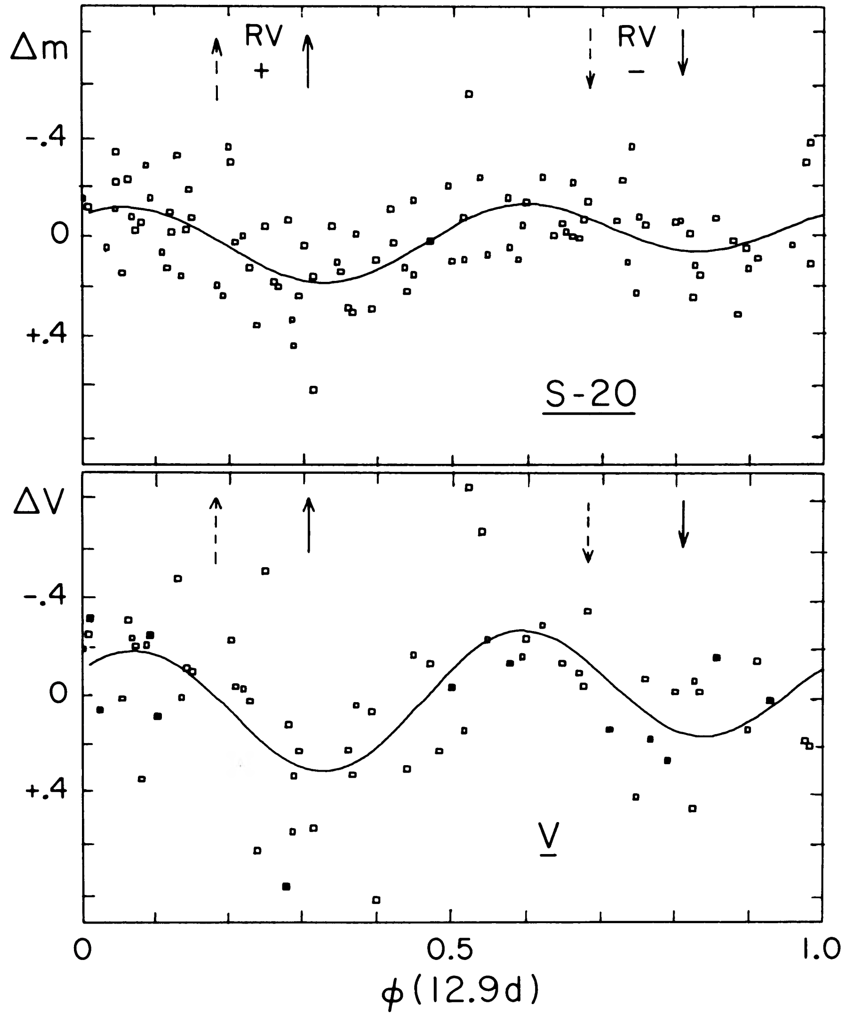

FIG. 3.—Unfiltered-light and V band data folded on the 12.9 day period, twice the best-fit period of 6.45 days from the power spectra of Fig. 2. Long-period variation has been subtracted out as for Fig. 2. WO points in the V curve are the filled boxes. Starting epoch (phase 0.0) is JD 2,444,068.5, but an equivalent central epoch (see text) is JD 2,444,145.9 based on $P = 12.9$ days. Maximum positive radial velocity from CCH is indicated by upward arrows, determined by advancing from their central epoch to ours using $P = 13.1$ days (*solid arrows*) or $P = 12.9$ days (*dashed arrows*); see text. Fitted curves are sums of first and second harmonics.

Concerning the 13 day light curve (Fig. 3), the curve is double-peaked. Such double light curves are known in close binaries without eclipses, or with grazing eclipses; examples are the X-ray binary Cygnus X-1 and the classic system AO Cassiopeia. The differences between the two minima and maxima in our folded curves are marginal, and we cannot identify the fundamental or double period (13 days) from our data alone, without using the radial-velocity evidence (CCH).

Subsequent to our first writing of this *Letter*, two other sets of photometric data have been reported, by Gladyshev *et al.* (1979) and by Giles *et al.* (1980). Those observations were roughly contemporaneous with ours. To a first approximation our 13 day light curves resemble theirs, but they arrive at different values for the best-fit periods. The best-fit period in the Gladyshev *et al.* (1979) data is close to 12.75 days, based on their determination and on our own evaluation of some of their data. Giles *et al.* (1980; see also Giles 1979) claim a best period of 11.8 days. We thus can list four slightly different periods: 13.1 days (Crampton, Cowley, and Hutchings 1980); 12.9 days (this paper); 12.8 days (Gladyshev *et al.* 1979); and 11.8 days (Giles *et al.* 1980). Obviously the precise period will remain in doubt until data from the 1980 observing season become available.

There seems no question that a binary-like light curve with full period of 12–13 days exists, but the structure is perturbed by other effects, including an interaction with the 164 day process. In that connection we might look for side-band periods in the light variation, with either of the periods $(13^{-1} \pm 164^{-1})^{-1}$. Since tilted disks tend to antiprecess relative to the binary orbit, we would favor the shorter of those shifted periods, i.e., about 12.1 days. The sidereal and synodic periods may coexist in the data, and in finite data strings will not be completely decoupled by Fourier analysis. One may tend to see an intermediate best-fit period, which could partly explain the period disagreements between the several observing groups.

The 13/6.5 day light variations seem to be largely attributable to the continuum rather than to line-intensity changes. In the unfiltered (S-20) band, the mean equivalent width of the stationary Hα line is about 500 Å, and there is variation over the approximate range 180–800 Å (Margon 1979). Such variation is diluted by a factor of at least 5 in our passband of 2800 Å. (Other lines are much weaker.) The Hα equivalent-width changes, even if correlated with the 13 day period, would seem to account for at most a 25% contribution to the variation amplitude in the S-20 band. In the *V* band the interfering line Hβ^+ has an equivalent width which seems always less than 200 Å; the band being 800 Å wide, again less than 25% of the observed photometric amplitude could be attributed to the line. We hope later to carry out spectrophotometry in stationary Hα, while sampling an adjacent line-free region.

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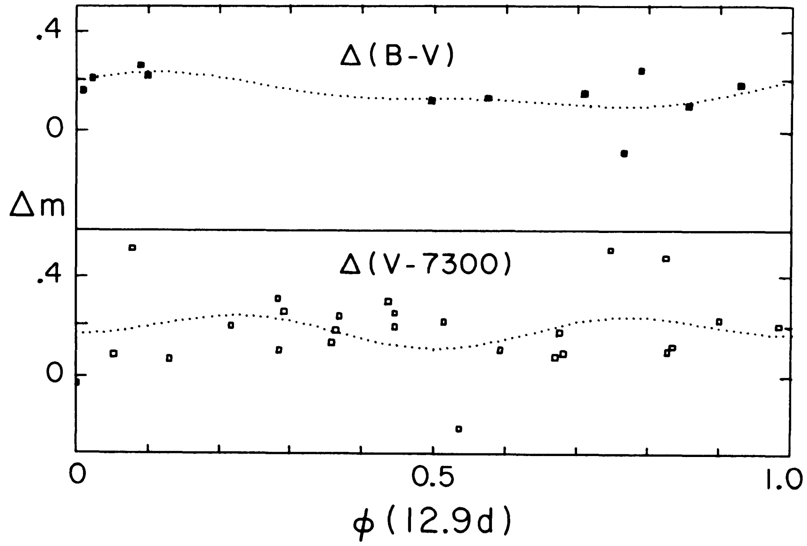

FIG. 4.—Color variations folded on our best-fit double period; same epoch and same vertical scale as in Fig. 3 but with arbitrary vertical displacements. Upper curve is WO data; lower is from PMO, using *V* and a special far-red band. Lower curve suggests a very small reddening (between *V* and λ7300) of 0.1 mag at light minima of the 13/6.5 day cycle.

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Note added in proof.—Margon, Grandi, and Downes (1980, preprint) now report a 13 day variation in the strength of the stationary Balmer lines. Their variation is partly double-peaked, but the main component is the fundamental period rather than the half-period. That agrees with the presence of a small fundamental-period term in our fitted curve (upper Fig. 3), in view of the presence of Hα in our S-20 band; but the continuum produces strong double peaking. Separately, Hut and van den Heuvel (1980, preprint) raised the question of an alias near 0.5 days. Our results from analyzing the slopes (§ III) rule out half-day and shorter aliases even more strongly than a 1 day alias.

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