

## ROTATION OF FK COMAE

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## ABSTRACT

$V \sin i$  for the rapidly rotating G-type giant FK Com is estimated using high-resolution coude spectra and the Fourier transform approach. The result,  $V \sin i = 159 \pm 4 \text{ km s}^{-1}$ , agrees well with recent determinations which used direct comparison of FK Com spectra with those of artificially broadened standards.

If FK Com does not differ drastically in its internal structure from more normal stars, its angular momentum is a few (perhaps 10) times larger than for single rapidly rotating stars following standard relations for the upper main sequence. Its angular momentum is about 3 times smaller than that of the orbital motion in a typical W UMa-type system.

**Key words:** Stellar rotation—giant star—stellar evolution—data-handling techniques

## 1. Introduction

FK Comae (HD 117555) is a unique, rapidly rotating, single, G-type giant, a prototype of a small group of rapidly rotating late-type giants which includes objects like HD 199178, HD 32918 (Bopp 1981; Collier 1982), or I-1 in NGC 188 (Harris and McClure 1985). It is a most extreme member of this group, with the largest rotational velocity and shortest rotational period. The origin of FK Comae-type stars is a matter of intensive research: They originate either from early type, rapidly rotating, single stars as they evolve into the giant domain (Fekel 1988; Simon and Drake 1989) or else they result from merging of close (W Ursae Majoris-type) binary systems (Bopp and Rucinski 1981; Bopp and Stencel 1981). Whatever the mechanism of formation is, such stars must have entered into the present state relatively recently, as their magnetic braking should be very strong: They possess extensive convective zones and are known to be very active magnetically. In fact, activity-related, nonthermally supported emission of FK Com has been observed in all accessible bands (Bopp and Stencel 1981) from X-rays (Walter 1981) to the radio domain (Hughes and McLean 1987).

Although it is possible that FK Com is in fact a tidally synchronized very close binary (Walter and Basri 1982; Walter *et al.* 1984), lack of any observable velocity changes larger than  $5 \text{ km s}^{-1}$  (McCarthy and Ramsey 1984) strongly suggests that, to be a binary, FK Com would have to have a very small mass ratio ( $q < 0.025$ ). It

is doubtful if a small companion would be able to enforce synchronism of a yellow giant during the relatively short available time of this evolutionary stage. It is obvious that in order to learn about the nature of the system we should know as many of its parameters as possible. Among such parameters the most prominent role is occupied by the projected equatorial velocity,  $V \sin i$ . We know that in the case of FK Com this velocity is extremely large for a G-type giant, but its value is poorly known at present. The reason for that is simple: There are practically no isolated lines in the rich spectrum of the late G-type giant. Apparently for this reason Bopp and Stencel (1981) used the strong and very wide (full width about  $12 \text{ \AA}$ ) Mg II 2800  $\text{\AA}$  emission to infer—via the Slettebak *et al.* (1975) calibration (applicable really to visual-region lines)—the rotational velocity  $120 \pm 20 \text{ km s}^{-1}$ . It was not clear whether this velocity represented the rotation field in the photosphere or in higher levels but it was not far from the previous estimate of Merrill (1948),  $75 \text{ km s}^{-1}$ , which was based on the broadening of photospheric absorption lines. We should note that the chromospheric H $\alpha$  emission in FK Com is much wider than that, extending over  $1000 \text{ km s}^{-1}$  or more (Bopp 1981; Bopp and Stencel 1981). Walter *et al.* (1984) analyzed widths and strengths of other chromospheric and transition lines noting that such lines are also very wide. Their estimate of the photospheric velocity was more than  $200 \text{ km s}^{-1}$ .

This wide range of estimates for the equatorial rotation ( $75, 120, >200 \text{ km s}^{-1}$ ) was noted by Ramsey *et al.* (1984) who found  $160 \pm 10 \text{ km s}^{-1}$  on the basis of their high S/N spectra. This has been improved subsequently by Buzasi (1987) to  $164.5 \pm 5.0 \text{ km s}^{-1}$ . However, the most popular

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value of  $120 \pm 20 \text{ km s}^{-1}$  is still frequently cited. We should stress that, because of the uniqueness of FK Com, the value of  $V \sin i$  is not of solely academic importance. Since we know the rotational period of the star (2.40 days) from the spot modulation, an accurate estimate of  $V \sin i$  can set an important constraint on the value of the radius and rotational angular momentum of the star.

This note describes measurements based on the Fourier domain techniques, somewhat in the spirit of numerous studies of Gray (1973, 1975, 1976, 1988). The main difference relative to his works is that the rotational signature is searched for not in a single, well-defined line—such lines are simply not present in the spectrum of FK Com—but rather in a spectrum segment about  $60 \text{ \AA}$  wide. The observations and their analysis are described in Sections 2 and 3. Section 4 contains a discussion of the results.

## 2. Observations

High-resolution spectral observations of FK Com were obtained with the Canada-France-Hawaii telescope in April 1988. The coudé Reticon-1872 system was used providing resolution of  $0.035 \text{ \AA}$  per diode (about  $2 \text{ km s}^{-1}$ ) in the region centered on the Mg I triplet at  $5175 \text{ \AA}$ . The spectra were flat fielded and wavelength calibrated in the usual manner and then resampled to equal velocities at exact  $2 \text{ km s}^{-1}$  spacing with the origin of the heliocentric velocity scale at  $5171 \text{ \AA}$ . About 200 pixels at the long-wavelength end had to be removed because of the unreliable shutter mechanism which sometimes partly covered the diodes. Thus, 1650 data points extending over  $3300 \text{ km s}^{-1}$  in radial velocity were finally used.

The list of the observation times is given in Table 1. The phases given there have been computed from the Chugainov (1976*a,b*) ephemeris which—confirmed by numerous subsequent photometric papers on FK Com—apparently still serves very well and has become a standard in studies of this star<sup>1</sup>. Each exposure lasted 40 minutes. The signal-to-noise ratio for the last two spectra was lower due to clouds (poor weather prevailed at CFHT during April 1988). The four spectra are shown in Figure 1.

The observations of FK Com were done as a side project in a larger program aimed at obtaining Fourier-deconvolved broadening profiles for W UMa-type systems. This program required that a few, slowly rotating standard stars also be observed at high S/N. Thus, in addition to a number of G-type dwarfs, two giants,  $\beta$  Corvi (G5 III,  $V = 2.6$ ,  $(B - V) = 0.89$ ,  $V \sin i = 3.8 \text{ km s}^{-1}$ ) and  $\beta$  Herculis (G8 III,  $V = 2.8$ ,  $(B - V) = 0.94$ ,  $V \sin i = 2.2 \text{ km s}^{-1}$ ), were also observed to S/N about 150–200. These two stars could be reasonable nonrotating analogs of FK Com whose spectrum is notoriously difficult to classify

<sup>1</sup>This stability being the main reason for the binary hypothesis of FK Com.

TABLE 1  
CFHT Coudé-Reticon Observations of FK Comae  
April 1988

| Number | JD (hel)<br>2 447 250+ | Phase | S/N |
|--------|------------------------|-------|-----|
| 1      | 0.853                  | 0.712 | 75  |
| 2      | 1.096                  | 0.813 | 75  |
| 3      | 2.786                  | 0.517 | 50  |
| 4      | 4.131                  | 0.078 | 40  |

and has been given before as: G5 II, gG8pe, C0pn, G2 IIIa, G8 IV (for references, see Bianchi, Grewing, and Kappelman 1985). Judging by the color indices (Rucinski 1981; Morris and Milone 1983; Holtzman and Nations 1984), the spectral distribution corresponds to the cooler end of the above-cited range of spectral types, at about G8 III ( $0.85 < (B - V) < 0.90$ ). In the next section we will show results for one spectrum of  $\beta$  Crv as a reference case of a slowly rotating star.

## 3. Analysis

The spectra have been analyzed using the Fourier transform formalism. At first, attempts were made at obtaining rotational profiles of FK Com by the full treatment of the Fourier deconvolution, i.e., via division of complex transforms, filtering, and the inverse transform. It became quickly obvious that such an approach is strongly dependent on the somewhat subjective decisions on the filtering. Whereas the high-frequency end can be treated by some variants of the optimum-filter techniques, the resulting profiles depended also on a few low-frequency components which indicated that spectra of FK Com and standard stars did not match very well. This is not surprising since the Mg I triplet may be strongly dependent on the presence and strength of the chromosphere, which we know is very strong in FK Com.

In this situation it was decided to stay in the Fourier domain and search for signatures of rotation only in the frequency space. As described in Gray's papers (cf. references in the Introduction), rapid rotation shows a very clear signature in this space in the form of side lobes, with the first side lobe invariably about 10% of the main peak. Minima between lobes are well-defined and their positions depend in a simple manner on the value of  $V \sin i$ . The dependence on the assumed limb darkening in the lines is weak and does not exceed a few percent.

The Fourier amplitudes for individual spectra are shown in Figure 2. The amplitudes have been computed from  $a = \sqrt{t \cdot \text{conj}(t)}$ , where  $t$  is the complex Fourier

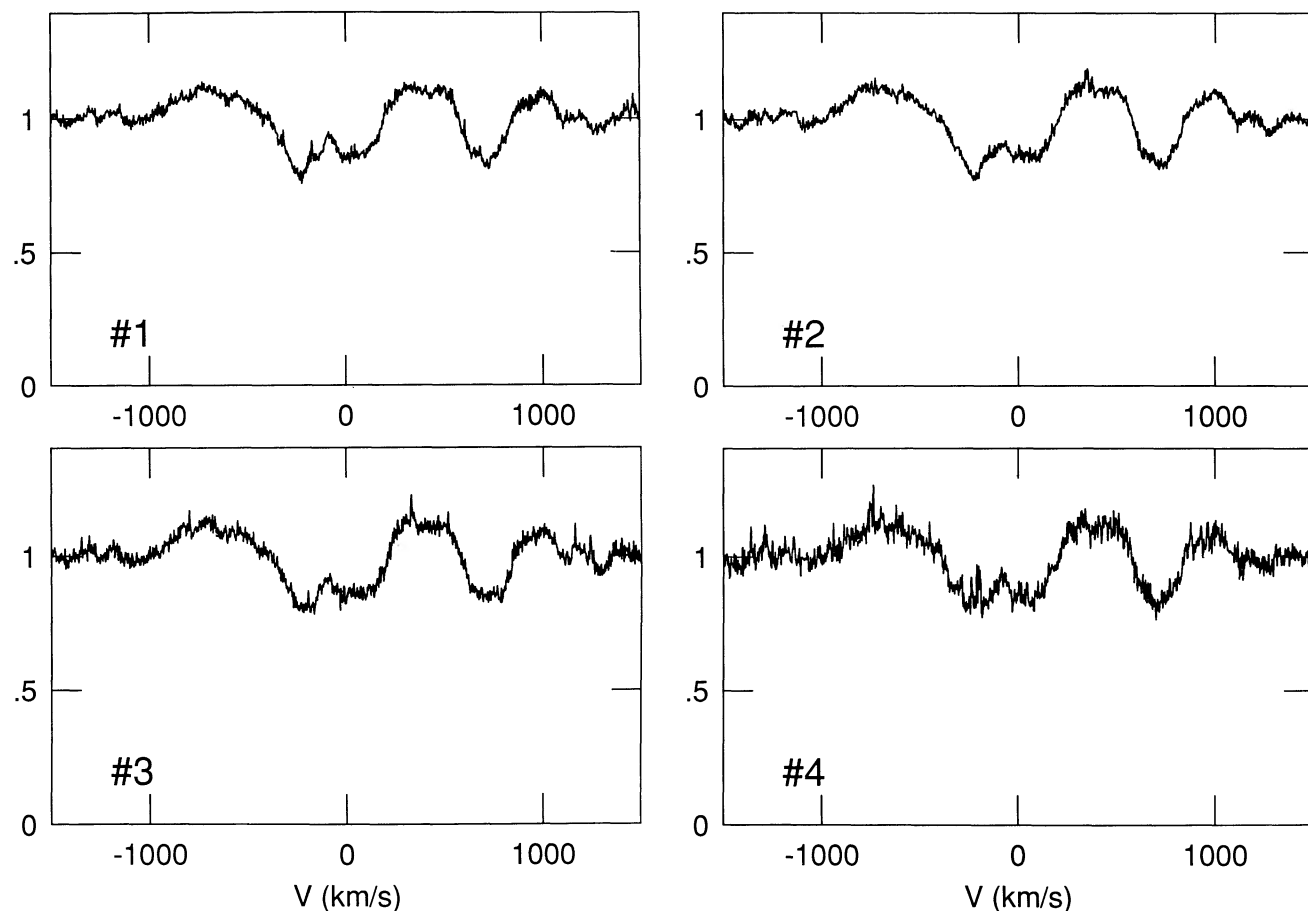


FIG. 1—The four spectra used to determine  $V \sin i$  of FK Com. The spectra cover about  $60 \text{ \AA}$  around the Mg I triplet. The radial-velocity scale (in  $\text{km s}^{-1}$ ) has its origin at  $5171 \text{ \AA}$ . The dates and times are listed in Table 1.

transform of the spectrum. Inspecting Figure 2 one can easily see the lobe structure which can be used to derive  $V \sin i$ . For comparison, Figure 3 shows a typical spectrum of  $\beta$  Crv and its Fourier amplitude function. Notice that frequencies that we consider here are, in fact, quite low and that the amplitude function,  $a$ , for the rich spectrum of  $\beta$  Crv is relatively flat in this region.

Since the shape of  $a$  for rotation alone is independent of  $V \sin i$  in the log-log plots, the determination of  $V \sin i$  can be performed by finding the shift necessary to fit the observed amplitudes by the theoretical function  $a$ . Such a function can be easily obtained by calculating a Fourier transform of the rotational-broadening profile:  $g = c_1(1 - x^2)^{1/2} + c_2(1 - x^2)$ . Here  $x = v/V \sin i$ , and the coefficients  $c_i$  depend on the limb-darkening coefficient,  $u$ :  $c_1 = 2(1 - u)/(1 - u/3)/\pi$  and  $c_2 = u/(1 - u/3)/2$ . ( $g$ , as given above, should be normalized to unity for convolutions.) The fits have been performed using a mean amplitude function, obtained by weighted averaging of such functions for the four spectra that we had. The solutions depend slightly on how many frequencies are included in the fits. Inclusion of higher lobes should, in principle, better constrain the solution, but then noise starts to add

up and tends to pull solutions upward along the vertical axis (Fig. 4). Fortunately, different assumptions on the number of included lobes do not seem to produce significant shifts in the horizontal (frequency) axis and therefore do not affect the resulting value of  $V \sin i$ . This can be verified in Table 2 where the results are listed. For each fit, an estimate on the error in  $V \sin i$  comes from the widths of the  $\chi^2$  function produced by the fitting process. These errors agree with those obtained from experiments with artificially broadened spectra of  $\beta$  Crv and  $\beta$  Her for which we were able to recover the assumed  $V \sin i$  to about  $\pm 2 \text{ km s}^{-1}$ . As is customary,  $u = 0.6$  was assumed for most solutions due to the lack of knowledge on the limb darkening for lines contributing in the spectrum. However, the continuum limb darkening in this spectral region and at this spectral type is actually slightly larger,  $u \approx 0.7\text{--}0.75$  (Wade and Rucinski 1985). As can be seen in Table 2, assumption of a larger limb darkening has a negligible influence on the results.

#### 4. Conclusions

The projected equatorial velocity of FK Com determined using the Fourier amplitude approach is  $V \sin i =$

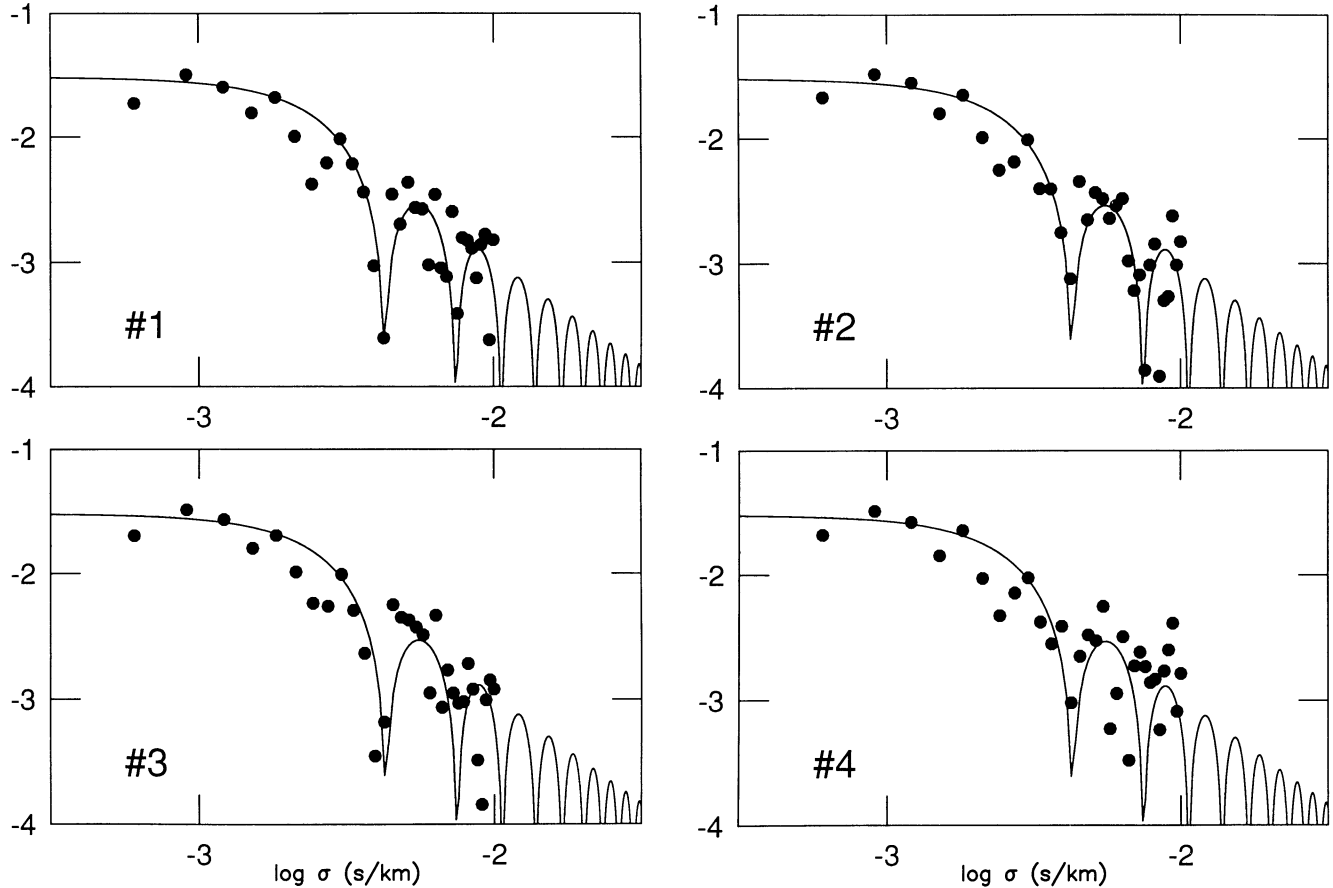


FIG. 2—The Fourier amplitudes for the four spectra of FK Com. The horizontal scale is in log of frequency, expressed in  $\text{s km}^{-1}$ ; the vertical scale is in log of intensity amplitude. The continuous line gives the final fit to the mean amplitude function (Fig. 4).

$159 \pm 4 \text{ km s}^{-1}$ . This result agrees very well with the most recent determinations of  $160 \pm 10 \text{ km s}^{-1}$  and  $164.5 \pm 5 \text{ km s}^{-1}$  by Ramsey *et al.* (1984) and Buzasi (1987) which used an entirely different approach of comparing spectra of FK Com with artificially broadened spectra of slowly rotating standards.

Using the above value of  $V \sin i$  and assuming the photometric period of 2.4 days for the rotation period, we arrive at the lower limit to the equatorial radius of FK Com:  $R > 7.3 \pm 0.2 R_{\odot}$ . Since we see an obvious and strong light modulation presumably coming from spots, indicating that the inclination  $i$  is close to  $90^{\circ}$ , this limit is probably not far from the actual radius of FK Com. We can use this number to estimate the angular momentum. We will assume solid rotation which is the simplest and most reasonable assumption in late-type stars where turbulent convection is the source of large viscosity. Thus,  $J = M\Omega(kR)^2$ . Normalizing to the Sun, we obtain:  $(J/J_{\odot})_{\text{FK}} > (580 \pm 30) (\mathcal{M}/\mathcal{M}_{\odot}) (k/k_{\odot})^2$ . We know neither the mass of FK Com nor its radius of gyration,  $k$ , so that these uncertainties will remain in all further considerations. Note, however, that Guinan and Robinson (1986) estimated the age of FK Com on the basis of kinematic

information. This estimate leads to a crude limit on the mass of the star of about  $1\text{--}1.5 \mathcal{M}_{\odot}$ .

The lower limit to the amount of angular momentum,  $(J/J_{\odot})_{\text{FK}}$ , which we have estimated above may seem to be quite large. We should remember, however, that it is normalized to the very slowly rotating Sun. More meaningful would be comparisons with a typical W UMa system and a rapidly rotating star in the upper part of the main sequence.

First, we will attempt to estimate if a single, rapidly rotating star from the main sequence could, without any loss of angular momentum, evolve in FK Com. The best estimate for the angular momentum of upper-main-sequence stars comes from the recent determination by Kawaler (1987). Normalizing to the Sun using  $\log(J/M)_{\odot} = 14.85 \text{ cgs}$  (Rucinski 1988), we obtain a simplified relation for the upper main sequence:  $(J/J_{\odot})_{\text{UMS}} \approx 68(\mathcal{M}/\mathcal{M}_{\odot})^2$ . If we compare this number with the limit on  $(J/J_{\odot})_{\text{FK}}$  given above we can see that, apparently, FK Com has a few ( $> 8$ ) times more angular momentum than a typical rapidly rotating main-sequence star, especially if its mass is indeed close to that of the Sun. Thus, without a very drastic restructuring of the star, it would be impossible to

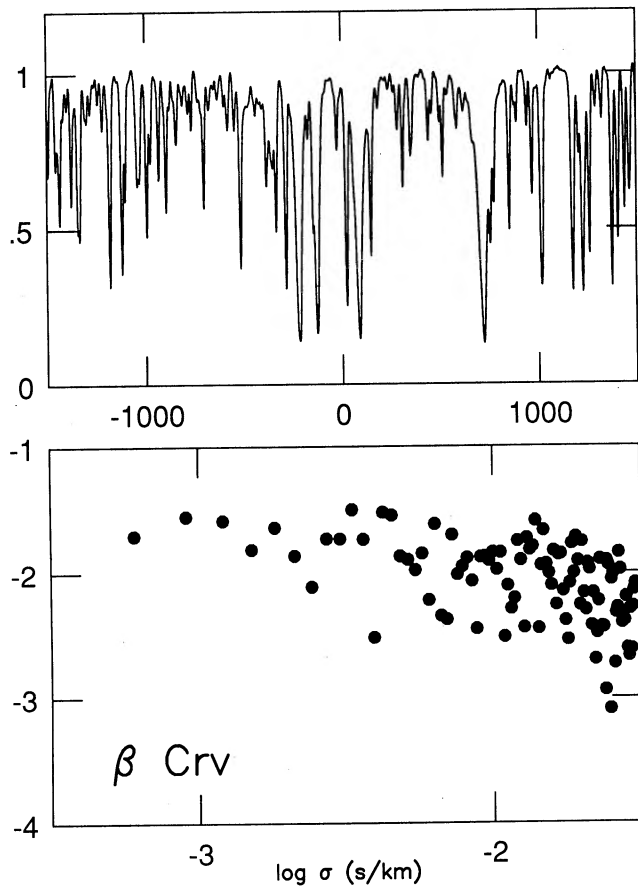


FIG. 3—The spectrum (upper panel) and the corresponding Fourier amplitude function (lower panel) for  $\beta$  Crv, a normal, slowly rotating giant. See Figures 1 and 2 for more detailed explanations.

convert a single, rapidly rotating main-sequence star in FK Com.

For a comparison with a typical W UMa system, we will take one with the total mass  $M_{\text{tot}} = 1.5 M_{\odot}$ , mass-ratio  $q = 0.3$  and period 0.3 day. The orbital angular momentum of such a system is:  $(J/J_{\odot})_W \approx 400 (M_{\text{tot}}/M_{\odot}) q / (1 + q)^2 k^2_{\odot} \approx 600 \times 0.18 / k^2_{\odot}$ . Using the best guess for the Sun of  $k^2_{\odot} \approx 0.05$  (Rucinski 1988), we obtain  $(J/J_{\odot})_W \approx 2100$ . By comparing the lower limit for  $(J/J_{\odot})_{\text{FK}}$  with this number, we come to the conclusion that a typical W UMa system has about 3 times more angular momentum in its orbital

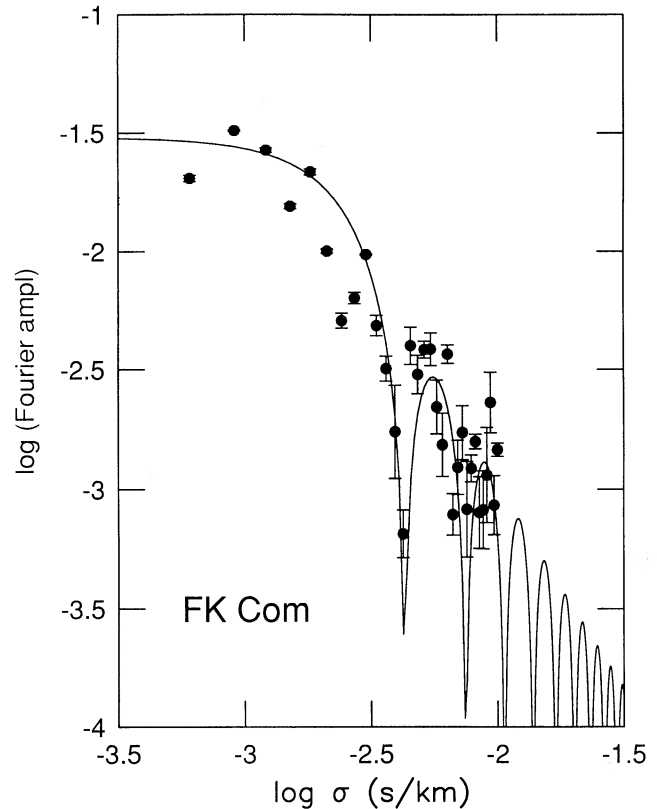


FIG. 4—Results of the weighted fit of the theoretical amplitude function for pure rotation to the mean amplitude function of FK Com. The latter has been formed from individual amplitude functions shown in Figure 2 with errors ( $\pm 1$  rms error) reflecting the spread in amplitude for each frequency  $\sigma$ . For some points the error bars are hidden inside the symbols. The particular fit shown here is based on data points belonging to the main lobe and the first side lobe (cf. Table 2).

motion than FK Com (actually less because we have the lower limit for FK Com). A very modest loss of angular momentum for FK Com could easily reconcile these numbers. In short, the W UMa-system merger remains as the more promising scenario for formation of FK Com.

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TABLE 2  
Results of the  $V \sin i$  Determinations for FK Comae ( $\text{km s}^{-1}$ )

| Type of fit           | $u = 0.6$   | $u = 0.75$  |
|-----------------------|-------------|-------------|
| Main lobe             | $164 \pm 7$ |             |
| Main + one side-lobe  | $159 \pm 4$ | $160 \pm 4$ |
| Main + two side-lobes | $156 \pm 6$ |             |

## REFERENCES

- Bianchi, L., Grewing, M., and Kappelman, N. 1985, *Astr. Ap.*, **149**, 41.
- Bopp, B. W. 1981, in *Second Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, ed. M. S. Giampapa and L. Golub, Smithsonian Astrophysical Observatory Special Report 392, p. 207.
- Bopp, B. W., and Rucinski, S. M. 1981, in *Fundamental Problems in the Theory of Stellar Evolution*, ed. D. Sugimoto *et al.* (Dordrecht: Reidel), p. 177.
- Bopp, B. W., and Stencel, R. E. 1981, *Ap. J. (Letters)*, **247**, L131.
- Buzasi, D. L. 1987, in *Cool Stars, Stellar Systems and the Sun*, ed. J. L. Linsky and R. E. Stencel (Berlin: Springer-Verlag), p. 518.
- Chugainov, P. F. 1976a, *Izv. Krym. Astrofiz. Obs.*, **54**, 89.
- . 1976b, *Izv. Krym. Astrofiz. Obs.*, **55**, 85.
- Collier, A. 1982, *M.N.R.A.S.*, **200**, 489.
- Fekel, F. C. 1988, in *A Decade of UV Astronomy with the IUE Satellite*, ESA SP-281, Vol. 1, p. 331.
- Gray, D. F. 1973, *Ap. J.*, **184**, 461.
- . 1975, *Ap. J.*, **202**, 148.
- . 1976, *The Observation and Analysis of Stellar Photospheres* (New York: Wiley).
- . 1988, *Lectures on Spectral-Line Analysis: F, G, and K Stars* (Arva, ON: The Publisher).
- Guinan, E. F., and Robinson, C. R. 1986, *A.J.*, **91**, 935.
- Harris, H. C., and McClure, R. D. 1985, *Pub. A.S.P.*, **97**, 261.
- Holtzman, J. A., and Nations, H. L. 1984, *A.J.*, **89**, 391.
- Hughes, V. A., and McLean, B. J. 1987, *Ap. J.*, **313**, 263.
- Kawaler, S. D. 1987, *Pub. A.S.P.*, **99**, 1322.
- McCarthy, J. K., and Ramsey, L. W. 1984, *Ap. J.*, **283**, 200.
- Merrill, P. W. 1948, *Pub. A.S.P.*, **60**, 382.
- Morris, S. L., and Milone, E. F. 1983, *Pub. A.S.P.*, **95**, 376.
- Ramsey, L. W., Barden, S. C., Huenemoerder, D. H., and McCarthy, J. K. 1984, *Bull. AAS*, **16**, 511.
- Rucinski, S. M. 1981, *Astr. Ap.*, **104**, 260.
- . 1988, *A.J.*, **95**, 1895.
- Slettebak, A., Collins, G., Boyce, P., White, N., and Parkinson, T. 1975, *Ap. J. Suppl.*, **29**, 137.
- Simon, T., and Drake, S. A. 1989, *Ap. J.*, **346**, 303.
- Wade, R. A., and Rucinski, S. M. 1985, *Astr. Ap. Suppl.*, **60**, 471.
- Walter, F. M. 1981, *Ap. J.*, **245**, 677.
- Walter, F. M., and Basri, G. S. 1982, *Ap. J.*, **260**, 735.
- Walter, F. M., Neff, J. E., Bopp, B. W., and Stencel, R. E. 1984, in *Cool Stars, Stellar Systems, and the Sun*, ed. S. L. Baliunas and L. Hartmann (Berlin: Springer-Verlag), p. 279.