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# STELLAR ACTIVITY IN SYNCHRONIZED BINARIES. I. DEPENDENCE ON ROTATION

GIBOR BASRI[1] AND ROBERT LAURENT
Astronomy Department, University of California, Berkeley
AND
FREDERICK M. WALTER[2]
Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder
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## ABSTRACT

We have examined a large sample of late-type binaries with orbital periods from 1 to 100 days for relationships between stellar activity and rotation period, which we assume (with a few exceptions) to be synchronized with the stellar orbital period. Most of the systems are in the RS Canum Venaticorum class of close binaries; none are contact binaries. The activity diagnostics were observed with the *International Ultraviolet Explorer* (*IUE*) and *Einstein Observatory* and range from the mid-chromosphere to the corona. Because these stars have some variation of stellar parameters with orbital period, we examine a number of different means of representing rotation-activity relations. We find that total luminosity is an ambiguous measure of activity in this sample; use of surface fluxes yields a relatively weak dependence of activity on rotation in the chromosphere, and a linear dependence in the corona. We compare our results with those for the single stars, and argue that the differences are not very great for the dwarfs, while the subgiants are at most an order of magnitude more active in the chromosphere when compared with appropriate single stars. No clear preference for period or velocity as a measure of rotation is found, although velocity reduces the differences with the single stars.

*Subject headings:* stars: binaries — stars: chromospheres — ultraviolet: spectra

## I. INTRODUCTION

A possible correlation between rotation and chromospheric activity was pointed out by Kraft (1967). The physical hypothesis suggested is that late-type stars likely have magnetic fields generated by a dynamo mechanism, that field production depends in part on forces generated by rotation, and that stellar activity is directly influenced by the presence of emerging magnetic flux. It must be admitted that this chain of reasoning has several weak points. In the first place, most dynamo models are more sensitive to the amount of differential rotation in the convection zone than to the surface rotation (which is the observed parameter). Second, it is not obvious that total magnetic flux generated will have a direct impact on the chromospheric emission observed. The observed emission could depend instead on the concentration of surface fields into active regions, or the extent to which the field is concentrated into small intense flux tubes, or on how the energy is dissipated. Furthermore, one might get saturation of the emission as the field continues to increase, or a nonlinear dependence of field and emission. It is also quite possible that some nonmagnetic agents (like acoustic waves) play a significant role in the heating of at least the lower chromosphere, which might or might not have a bearing on an apparent rotation-activity connection. Despite these concerns, many recent studies have confirmed the existence of clear correlations. Among these are the coronal relations found by Walter and Bowyer (1981) for RS Canum Venaticorum systems and by Pallavicini *et al.* (1981) and Schrijver, Mewe, and Walter (1984) for mostly single stars, and the chromospheric relations of Middlekoop (1981) and Noyes *et al.* (1984). A preliminary report on the work here appears in Basri, Laurent, and Walter (1983), and Skumanich and Eddy (1981) have discussed some general points relevant to this work.

We elected to study close-binary systems for a number of reasons. One of these is the existence of a large number of X-ray observations of these systems, which allows study of the relation between rotation and activity at all heights of the stellar atmosphere. The enhanced activity levels found in these systems mean that we can deal mostly with actual detections rather than upper limits, and they also allow detection of optically fainter stars with the *IUE*. Additionally, the generally synchronous nature of these systems coupled with the known orbital periods provides a ready-made source of rotation periods. When this study was initiated, the same was not true of typical field stars, although the Mount Wilson program of Ca II monitoring has greatly mitigated that problem. Finally, many of the active stars observed were of similar spectral type, eliminating one important potential source of confusion. We have examined not only members of the well-known RS CVn class but also other close binaries (generally less evolved) taken from the list of Young and Koniges (1977). The possibility that the close binaries might be intrinsically different in some way from the single field stars must always be kept in mind; Young and Koniges suggested, for example, that the enhanced activity in close binaries is due to tidal coupling.

## II. OBSERVATIONS AND STELLAR PARAMETERS

All the targets selected had at least one late-type star in the system, and were known to be chromospherically active. The periods for the systems were taken from Hall (1981) or Batten, Fletcher, and Mann (1978). These range from 0.7 days for ER Vul to 137 days for *o* Dra. There is a possible source of error in our periods, namely, the possible nonsynchronous nature of some of the systems. Middlekoop and Zwaan (1981) have argued that giants in systems with periods less than 120–200

[1] Guest Observer, *International Ultraviolet Explorer*.
[2] Guest Observer, *Einstein Observatory*.

days will be synchronized, and Middlekoop (1981) suggests that this limiting period is closer to 10 days for dwarfs in binaries. For most of the systems in our sample, synchronicity has actually been observed through the photometric periods owing to starspots (Hall 1981). In the two cases where the photometric period is different from the orbital period, we have used the former. One binary, $\xi$ Boo, is not an RS CVn system at all, since it is very wide, but the primary has a rotation period like that of an RS CVn star and is included for comparison.

To obtain a bolometric flux, we used estimates from the literature when available (Popper 1980; Popper and Ulrich 1977; Glebocki and Stawikowski 1979). Otherwise we used the visual magnitude and a bolometric correction obtained from Mihalas and Binney (1981) for each star in the system (when both are known) weighted by the relative contribution of each star to the total flux. When the spectral type of the secondary was unknown, we were sometimes able to discover it from the early-type contribution to the ultraviolet spectrum compared with spectra from the *IUE* Spectral Catalog (these are noted in Table 1). For systems which remained undetermined, we used the bolometric correction for the primary only. Since most of the bolometric corrections are relatively similar, this procedure should not be subject to large errors (perhaps 0.1 mag). We then converted to a bolometric flux; for systems with only one active component we calculated the flux due to that star alone.

Those were the only parameters required for our primary analysis. In order to compare with other work, however, we also computed other stellar parameters (albeit with greater uncertainty). We took stellar parameters from the literature mentioned above when given. A few systems have trigonometric parallaxes; otherwise we used given distance moduli or estimated them from spectral types. When not known, the effective temperatures were crudely estimated from spectral type, and a radius computed from these and the bolometric luminosity. Surface rotation velocities then followed from these and the periods. For systems with two active components, the radius and rotation velocity given are weighted averages, while the surface area given is the total for the active components. We expect that while the accuracy of these is reasonable in most cases, there could be fairly large uncertainties, especially in systems where the light is dominated by the earlier

TABLE 1

STELLAR PARAMETERS

| Star | Spectral Type | $P$ (days) | $l_{bol}$ ($10^{-7}$) | $D$ (pc) | $R$ (solar) | $V_r$ (km/s) | $A$ (solar) | Notes |
|---|---|---|---|---|---|---|---|---|
| ER Vul | G0 V + G5 V | 0.7 | 0.32 | 46 | 1.1 | 78 | 2.25 | |
| $\sigma$ CrB | F7 V + F7 V | 1.14 | 1.3 | 33 | 1.3 | 57 | 3.38 | |
| HD 155555 | G5 IV + K0 IV–V | 1.7 | 0.64 | 45 | 2.3 | 54 | 3.2 | |
| AR Lac | G2 IV + K0 IV | 2 | 1.2 | 49 | 3.1 | 66 | 12.8 | 1 |
| HR 1099 | G5 IV + K0 IV | 2.8 | 1.1 | 36 | 2.8 | 52 | 7.8 | |
| $\theta$ Dra | F8 IV–V | 3.1 | 6.4 | 14.5 | 1.8 | 30 | 3.24 | |
| TY Pyx | G5 IV + G5 IV | 3.2 | 0.59 | 57 | 1.65 | 27 | 5.5 | 1 |
| SZ Psc | F8 V + K1 IV | 3.9 | 0.24 | 89 | 4 | 51 | 16 | 1 |
| $\xi$ UMa | G0 V | 3.9 | 4.5 | 10 | 1.2 | 15 | 1.44 | 2 |
| Z Her | F4 V–IV + K0 IV | 4 | 0.16 | 82 | 2.6 | 33 | 6.8 | 1 |
| WW Dra | sgG2 + sgK0 | 4.6 | 0.15 | 168 | 3.1 | 34 | 20.5 | 1 |
| RS CVn | F V–IV + K0 IV | 4.8 | 011 | 147 | 4 | 43 | 16 | 1 |
| RT Lac | G9 IV + K1 IV | 5.1 | 0.1 | 271 | 4.45 | 43 | 39.7 | |
| AS Dra | G3 IV + K0 V | 5.4 | 0.38 | 57 | 2.5 | 21 | 13.2 | |
| UX Ari | G5 V + K0 IV | 6.4 | 0.83 | 57 | 3.3 | 26 | 15.4 | |
| $\Pi$ Peg | K2–K3 V–IV | 6.7 | 0.31 | 72 | 3.7 | 28 | 13.7 | |
| LX Per | G0 V + K0 IV | 8.1 | 0.12 | 119 | 2.8 | 18 | 7.8 | 1 |
| $\alpha$ Aur | F9 III + G6 III | 9 | 107 | 13.2 | 7.3 | 41 | 53.3 | 3 |
| 1 Gem | F5 V + G5 II | 9.6 | 6.6 | 56 | 12 | 63 | 144 | 4 |
| $\delta$ Tri | G0 V | 9.9 | 2.9 | 12.5 | 1.2 | 6 | 1.44 | |
| $\xi$ Boo | G8 V + K5 V | 10.5 | 3.6 | 6.8 | 0.8 | 4 | 0.64 | 3, 5 |
| 54 Cam | G0 + G0 | 11 | 0.72 | 36 | 1.2 | 5 | 2.88 | 3 |
| 42 Cap | G2 IV | 13.2 | 2.2 | 30 | 3 | 11 | 9 | |
| 6 Tri | G5 III + G5 III | 14.7 | 3.1 | 115 | 12 | 41 | 288 | 6 |
| 16 UMa | F9 V | 16.2 | 2.2 | 14.3 | 1.1 | 3.5 | 1.21 | |
| $\zeta$ And | K1 II + K0 V | 17.8 | 9.6 | 50 | 12.5 | 36 | 153 | |
| $\sigma$ Gem | K1 III | 19.6 | 7.9 | 59 | 15 | 39 | 225 | 6 |
| AR Mon | K0 III + K3 III | 21.2 | 0.14 | 470 | 12 | 19 | 318 | 2, 6 |
| HK Lac | F IV + K0 III | 24.4 | 0.9 | 130 | 15 | 31 | 222 | 6 |
| HR 8703 | K1 IV–III | 24.6 | 2.4 | 59 | 10 | 20 | 100 | 6 |
| HR 7275 | K1 IV | 28.6 | 1.6 | 57 | 8 | 14 | 64 | 6 |
| RZ Eri | Am + sgG8 | 39.2 | 0.2 | 233 | 13 | 17 | 169 | 2, 6 |
| $\lambda$ And | G8 IV–III | 53.7 | 9.2 | 30 | 7.9 | 7 | 62 | 3, 6 |
| HR 4665 | K0 III + K0 III | 64.4 | 2.7 | 130 | 15 | 12 | 444 | |
| 93 Leo | A3 V + G5 III | 71.7 | 2.8 | 79 | 14 | 10 | 190 | 4 |
| 33 Psc | A5 V + Ki III | 72.9 | 3.1 | 72 | 13 | 9 | 174 | 2, 4, 6 |
| 12 Cam | K0 III | 80.2 | 1.3 | 134 | 16 | 10 | 243 | 2, 6 |
| HR 7428 | A8 IV + K | 108.6 | 1 | 165 | 26 | 7 | 676 | 2, 6 |
| $o$ Dra | K0 III–II | 137.4 | 6.4 | 54 | 14 | 5 | 204 | 2 |

NOTES.—(1) Stellar parameters from Popper 1980. (2) Synchronization assumed. (3) Rotational period different from orbital period. (4) Spectral type of secondary estimated from *IUE* spectrum (5) Not a close binary; G star only. (6) Stellar parameters from Glebocki and Stawikowski 1979.

star or the spectral class is poorly known. Spectral class is also not a particularly good indicator of radius for the stars evolving through the Hertzsprung gap. A list of the known and derived stellar parameters is given in Table 1.

X-ray data were available for nearly all systems, and most were accessible to both *IUE* cameras within 2 hour exposures. The stars appearing here constitute the bulk of such targets available; a significant improvement in the statistics must await the Space Telescope era. The flux in a given line in the SWP spectra was obtained by measuring the area contained in the spectral region above the continuum or background levels, as has been the usual practice (e.g., Ayres, Marstad, and Linsky 1981). Reductions were accomplished with the SOL language on the Berkeley Astronomy Department VAX. For some of the weaker lines the percentage error is relatively large because of noise (30%–50%), while for strong lines such as C IV the errors are close to the systematic value of 10%–15%. In the case of N V (1240 Å), the presence of geocoronal Lyman-alpha sometimes rendered the continuum subtraction less certain. For observations of systems containing stars earlier than spectral type G, the spectra at wavelengths longer than 1500–1700 Å were sometimes saturated. This explains the fewer data points for some of the longer wavelength SWP diagnostics. We used the standard *IUE* calibration (Bohlin *et al.* 1981) for all low-dispersion spectra.

Whenever possible, we used high dispersion to observe the Mg II doublet. This yields both line profile and flux information (using the calibration of Cassatella, Ponz, and Sevelli 1981) and allows separation of the *k* and *h* lines and proper subtraction of the underlying continuum. Low-dispersion observations were forced by the faintness of some targets, and the abbreviated exposure times demanded during very high radiation shifts forced us to make a few others. Some of these latter targets were later repeated at high dispersion, allowing calibration of the errors in measuring the continuum-contaminated unresolved doublet at low dispersion.

The correction to be made for low dispersion depends on the type of profile intrinsically present. The low-dispersion mode blends the *h* and *k* lines, the intervening continuum, and some radiation from the outer wings and beyond. For stars in which the emission feature is quite strong or even stronger than the neighboring continuum, the errors from this blending can be relatively minor. In cases where the emission peaks were less than 20% of the adjacent continuum (which was often due to the earlier type star), no emission feature could be discerned at low dispersion. We were able to examine two strong and two weak cases, and derived rough conversion factors for the measured low-dispersion fluxes to actual core emission. These are rather uncertain, but were not found to affect our analysis significantly. A list of all the observed fluxes at the Earth is given in Table 2. Most of the observations are our own, but we have added other published data to the final list as noted. The observations are generally contemporaneous for a given star, with the exception of the X-ray fluxes.

## III. ANALYSIS

One has some freedom in the choice of variables with which to frame a "rotation-activity" relation. Rotation can be taken to mean either linear surface rotation velocity or angular velocity (or its inverse, the rotation period). Activity may also be taken to mean either total integrated luminosity in a chosen diagnostic, or a measure of surface flux in that diagnostic (usually expressed as a flux ratio between that diagnostic and bolometric luminosity). Pallavicini *et al.* (1981) use total luminosity versus linear velocity, while Walter and Bowyer (1981) and Noyes *et al.* (1984) use flux ratio versus period.

The essential difference between the two approaches is in the global versus local perspective; ideally surface fluxes tell one about conditions in individual flux tubes, while total luminosity says something about the total number of tubes, or total amount of nonradiative energy dissipation. Surface fluxes eliminate the effect of differing stellar radii, which are implicitly present in total luminosity measurements. Unless one knows whether giants and dwarfs look the same on a local basis (have similar looking flux tubes), comparison of activity between them is subject to ambiguities. Schrijver, Mewe, and Walter (1984) suggest, in fact, that their coronae are somewhat different in temperature and loop length.

Another important source of ambiguities is the lack of knowledge of the filling factors of activity. Unless these are fixed, it is difficult to tell whether differences in measured activity are due to changes in individual flux tubes or in the number or coverage of tubes. Surface fluxes contain implicit information on the filling factor which is not easily extracted without additional information on local conditions. We note that the choices of total or surface flux are essentially equivalent when only stars of the same spectral type are considered because they should all have the same surface area. Flux ratios are the logical equivalent of surface flux, with the additional benefit of eliminating most sources of uncertainty in stellar parameters. When the bolometric flux is used as the normalizing flux, there is the possible interpretation of the result as an efficiency of energy conversion to nonradiative heating. In order to maximize the information from our data we have considered all these possible modes of analysis; this has made clear to what extent there is a direct connection between rotation and activity.

Because of the somewhat inhomogeneous nature of our sample, we have subdivided the evolved RS CVn systems containing an active star later than G5 (usually a K subgiant), our largest homogeneous subsample, from the hotter subgiants. These are shown as solid and open squares, respectively, in the figures, and are noted in Table 1. There are 39 stars in the full sample, with 23 of these in the cool RS CVn subclass. We have additionally separated out the seven dwarfs, since they have substantially different internal structures and radii. These are shown as asterisks in the figures.

Our primary analysis consists of a standard least-squares fit using the log of the activity diagnostic as the dependent variable and the log of the period or rotation velocity as the independent variable, which results in power-law relations. The errors in the period are negligible compared with the errors in the flux ratio, apart from questions of nonsynchronicity. The errors in the rotation velocity are likely to be more substantial. Because the radii themselves are related to period for the subgiants, there is little distinction between period and velocity relations; we find analogous results for both with slightly more scatter in velocity, as might be expected from the intrinsic error. The sense of all rotation-activity relations is for increased activity in the more rapid rotators. We also examine the relative slope of such relations separately for the chromosphere, transition region, and corona. The slopes and reduced $\chi^2$ goodness-of-fit measures are tabulated for all relations in Table 3, along with the number of data points in each fit. For consistency we have listed fits for the subgiants only; we discuss the instances where exclusion of the dwarfs makes a

TABLE 2

OBSERVED FLUXES

| Star | Mg II ($10^{-12}$) | O I ($10^{-13}$) | C I ($10^{-13}$) | Si II ($10^{-13}$) | C II ($10^{-13}$) | C IV ($10^{-13}$) | Si IV ($10^{-13}$) | He II ($10^{-13}$) | N V ($10^{-13}$) | X-rays ($10^{-12}$) | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ER Vul | 4.4 | 0.6 | 3.3 | ... | 2.7 | 3.6 | 2.1 | 2.1 | 0.7 | 12.7 | |
| $\sigma$ CrB | 33.0 | 10.0 | 7.3 | 5.1 | 15.0 | 41.0 | 15.0 | 6.0 | ... | ... | |
| HD 155555 | 8.8 | 2.2 | 4.0 | 4.8 | 4.5 | 7.1 | 1.8 | 4.5 | 1.5 | 97.95 | 1 |
| AR Lac | 9.8 | 8.0 | 7.1 | 11.0 | 8.5 | 12.0 | 8.4 | 5.6 | 0.34 | 37.2 | |
| HR 1099 | 61.0 | 7.2 | 2.2 | 4.8 | 19.0 | 31.0 | 9.6 | 11.5 | 6.7 | 179 | 2 |
| $\theta$ Dra | 14.4 | 4.1 | 7.2 | ... | 6.5 | 8.2 | 5.6 | 0.8 | 2.6 | 4.5 | |
| TY Pyx | 6.8 | 1.6 | 4.3 | 2.8 | 3.3 | 7.0 | ... | 1.3 | 1.7 | 18.4 | 1 |
| SZ Psc | 6.7 | ... | 2.6 | 4.3 | 1.6 | 4.3 | ... | ... | 3.2 | 27.4 | 1 |
| $\xi$ UMa | 33.0 | 4.5 | 26.7 | ... | 8.1 | 10.6 | 6.7 | 7.7 | 2.4 | 31.5 | |
| Z Her | ... | 0.6 | 1.0 | ... | 0.8 | 1.9 | ... | 0.5 | 0.2 | 2.4 | |
| WW Dra | 0.8 | ... | ... | ... | ... | ... | ... | ... | ... | 2.2 | |
| RS CVn | 1.9 | ... | ... | ... | ... | ... | ... | ... | ... | 10.3 | |
| RT Lac | 5.5 | ... | ... | ... | ... | ... | ... | ... | ... | 17.3 | |
| AS Dra | 2.6 | ... | ... | ... | ... | ... | ... | ... | ... | 2.3 | |
| UX Ari | 17.0 | 10.0 | ... | 8.1 | 9.8 | 14.0 | 5.6 | 7.8 | 4.2 | 80 | 2 |
| II Peg | 9.6 | 4.9 | 4.1 | 4.8 | 5.2 | 9.6 | 10.4 | 7.6 | ... | 32.7 | |
| LX Per | 1.9 | ... | ... | ... | ... | ... | ... | ... | ... | 2.8 | |
| $\alpha$ Aur | 1400 | 500 | 120 | 510 | 270 | 440 | 230 | ... | 130 | 170 | 3 |
| 1 Gem | 6.2 | 1.1 | 3.6 | ... | 0.7 | 1.0 | ... | ... | ... | 0.32 | |
| $\delta$ Tri | 27.9 | 11.3 | 6.8 | ... | 5.2 | 9.6 | 7.6 | 4.5 | 4.3 | ... | |
| $\xi$ Boo | 28.6 | 2.6 | 6.3 | 11.7 | 4.8 | 5.3 | 3.8 | 4.6 | 2.3 | 18.6 | |
| 54 Cam | 3.8 | ... | 3.0 | ... | 1.5 | 4.2 | 3.1 | 1.6 | 0.4 | 5.5 | |
| 42 Cap | 8.2 | 3.0 | 1.1 | ... | 2.4 | 5.4 | ... | 1.6 | ... | ... | |
| 6 Tri | 9.1 | 3.8 | 3.7 | 9.2 | 1.8 | 2.7 | 1.4 | 0.6 | 0.9 | 1.04 | |
| 16 UMa | 1.9 | ... | 0.9 | ... | 0.6 | ... | ... | ... | ... | ... | |
| $\zeta$ And | 72.1 | 10.9 | 4.8 | 9.4 | 4.1 | 6.7 | 4.4 | 4.2 | 3.0 | 15.45 | |
| $\sigma$ Gem | 120.0 | 34.3 | 9.7 | 23.6 | 17.6 | 31.0 | 14.0 | 11.8 | 11.4 | 54.4 | 4 |
| AR Mon | 9.7 | ... | ... | ... | ... | ... | ... | ... | ... | 0.94 | |
| HK Lac | 11.4 | 4.7 | 2.3 | 3.3 | 2.7 | 3.0 | ... | 2.4 | 2.9 | 8.75 | 1 |
| HR 8703 | 30.7 | 17.6 | 7.0 | 13.1 | 7.3 | 18.7 | 12.5 | 6.3 | 7.9 | 17 | |
| HR 7275 | 13.7 | 11.0 | 6.9 | 8.5 | 6.4 | 9.2 | 4.4 | 3.8 | 2.7 | 17.95 | |
| RZ Eri | 6.2 | ... | ... | ... | ... | ... | ... | ... | ... | 2.8 | |
| $\lambda$ And | 160.0 | 40.0 | 11.0 | 9.5 | 13.0 | 26.0 | 13.0 | 15.6 | 5.0 | 63.1 | 5 |
| HR 4665 | 17.9 | 6.0 | 2.7 | 7.2 | 3.1 | 6.4 | 3.2 | 3.9 | 3.1 | 17.1 | |
| 93 Leo | 13.6 | 4.4 | ... | ... | 1.5 | ... | 3.0 | ... | 2.5 | 5.7 | |
| 33 Psc | 4.5 | ... | 1.2 | 3.1 | 0.8 | ... | ... | ... | ... | 0.1 | |
| 12 Cam | 18.7 | 11.0 | 6.6 | 6.6 | 1.8 | 6.0 | 9.9 | 2.5 | 3.0 | 5.1 | 1 |
| HR 7428 | 15.1 | 6.3 | ... | ... | 5.1 | 2.6 | 2.5 | ... | 1.8 | 9.8 | |
| $o$ Dra | 10.8 | 7.1 | 2.6 | 2.2 | 1.2 | 2.3 | ... | 1.7 | 0.9 | 0.12 | |

NOTES.—(1) Low-resolution Mg II data only. (2) Simon and Linsky 1980. (3) Ayres, Schiffer, and Linsky 1983. (d) Ayres, Simon, and Linsky (1984). (5) Baliunas and Dupree (1981).

difference. Note that although the formal slope is given in each instance, when the goodness-of-fit parameter is significantly larger than the slope, then one essentially has a scatter diagram.

### *a*) *Total Luminosity*

The first important fact about this sample of stars can be seen in the upper left-hand panel of Figure 1, which shows the bolometric luminosity for these stars as a function of period. As has been known for some time, there is a good correlation between period and luminosity in the evolving systems, which Young and Koniges (1977) ascribe to a tendency for the stars to try to fill their Roche lobes (although they do not fully accomplish this; cf. Glebocki and Stawikowski 1979). They predict a slope of 4/3 on this basis, while we find a slope of 3/4. Thus the longer period stars tend to be much larger and somewhat more luminous despite their lower effective temperatures. Several of the longer period systems contain an A star, indicating that they may be more massive on average. In any case the dependence of luminosity or radius on period obviously has an influence on rotation-activity relations (depending on how they are measured) but may have nothing to do with magnetic dynamos.

The remainder of Figure 1 shows that the dwarfs lie below the subgiants as expected, and exhibit a decrease of activity with increasing period as found in the single stars. The fits given in Table 3 are for the subgiants only. There is a tendency for positive slope with period for the total luminosity of most activity diagnostics in the subgiants, the slope being steepest for the chromospheric diagnostics and not present in X-rays. The other analyses in this paper point to the following explanation: there is an intrinsic dependence of activity on rotation in these stars which is relatively weak in the chromosphere and is amplified by activity correlation slopes (as in Ayres, Marstad, and Linsky 1981; Basri and Laurent 1983) to greater slopes in the transition region and corona. It is probably coincidental that the slope of this intrinsic coronal relation is just canceled by the opposite slope due to stellar radius. This is because the small rapid rotators have larger ratios of X-ray to bolometric luminosity, which results in there being no relation between total coronal luminosity and period for our sample. We make this interpretation because one does see some slope

TABLE 3

SLOPES AND FITS

| Relation | Mg II (31) | O I (23) | C I (22) | Si II (19) | C II (25) | C IV (23) | Si IV (17) | He II (19) | N V (21) | X-rays (31) | Bolometric (32) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Luminosity vs. period | 0.53 | 0.71 | 0.30 | 0.18 | 0.17 | 0.25 | 0.51 | 0.40 | 0.52 | −0.29 | 0.75 |
| | (0.58) | (0.51) | (0.49) | (0.45) | (0.52) | (0.49) | (0.44) | (0.61) | (0.54) | (0.88) | (0.37) |
| Luminosity vs. velocity | −0.25 | −0.61 | 0.06 | 0.18 | 0.03 | −0.10 | −0.58 | −0.03 | −0.40 | 0.68 | −0.58 |
| | (0.65) | (0.63) | (0.52) | (0.46) | (0.53) | (0.51) | (0.51) | (0.65) | (0.62) | (0.87) | (0.53) |
| Surface flux vs. period | −0.52 | −0.38 | −0.74 | −0.81 | −0.89 | −0.84 | −0.60 | −0.70 | −0.56 | −1.36 | −0.32 |
| | (0.43) | (0.44) | (0.38) | (0.29) | (0.47) | (0.50) | (0.44) | (0.52) | (0.45) | (0.68) | (0.17) |
| Surface flux vs velocity | 0.70 | 0.32 | 0.84 | 1.21 | 1.01 | 0.81 | 0.75 | 0.92 | 0.86 | 1.79 | 0.41 |
| | (0.47) | (0.48) | (0.51) | (0.39) | (0.63) | (0.65) | (0.52) | (0.60) | (0.49) | (1.01) | (0.21) |
| Flux/$l_{bol}$ vs. period | −0.19 | −0.03 | −0.44 | −0.52 | −0.56 | −0.50 | −0.23 | −0.39 | −0.22 | −1.04 | ... |
| | (0.47) | (0.48) | (0.44) | (0.33) | (0.53) | (0.55) | (0.51) | (0.60) | (0.51) | (0.91) | |
| Flux/$l_{bol}$ vs. velocity | 0.29 | −0.11 | 0.53 | 0.84 | 0.61 | 0.42 | 0.15 | 0.59 | 0.38 | 1.34 | ... |
| | (0.47) | (0.48) | (0.48) | (0.36) | (0.59) | (0.61) | (0.53) | (0.61) | (0.51) | (1.00) | |
| Flux/$f_{Mg\,II}$ vs. period | ... | 0.11 | −0.17 | −0.14 | −0.33 | −0.34 | −0.17 | −0.20 | −0.06 | −0.86 | ... |
| | | (0.23) | (0.38) | (0.35) | (0.25) | (0.25) | (0.34) | (0.34) | (0.32) | (0.58) | |
| Flux/$f_{Mg\,II}$ vs. velocity | ... | −0.22 | 0.16 | 0.26 | 0.31 | 0.26 | 0.11 | 0.18 | 0.06 | 1.09 | ... |
| | | (0.22) | (0.39) | (0.35) | (0.30) | (0.31) | (0.36) | (0.35) | (0.33) | (0.68) | |

NOTE.—Number of data points is shown in parentheses at the head of each column. Reduced $\chi^2$ goodness-of-fit measures are shown in parentheses under the slope values.

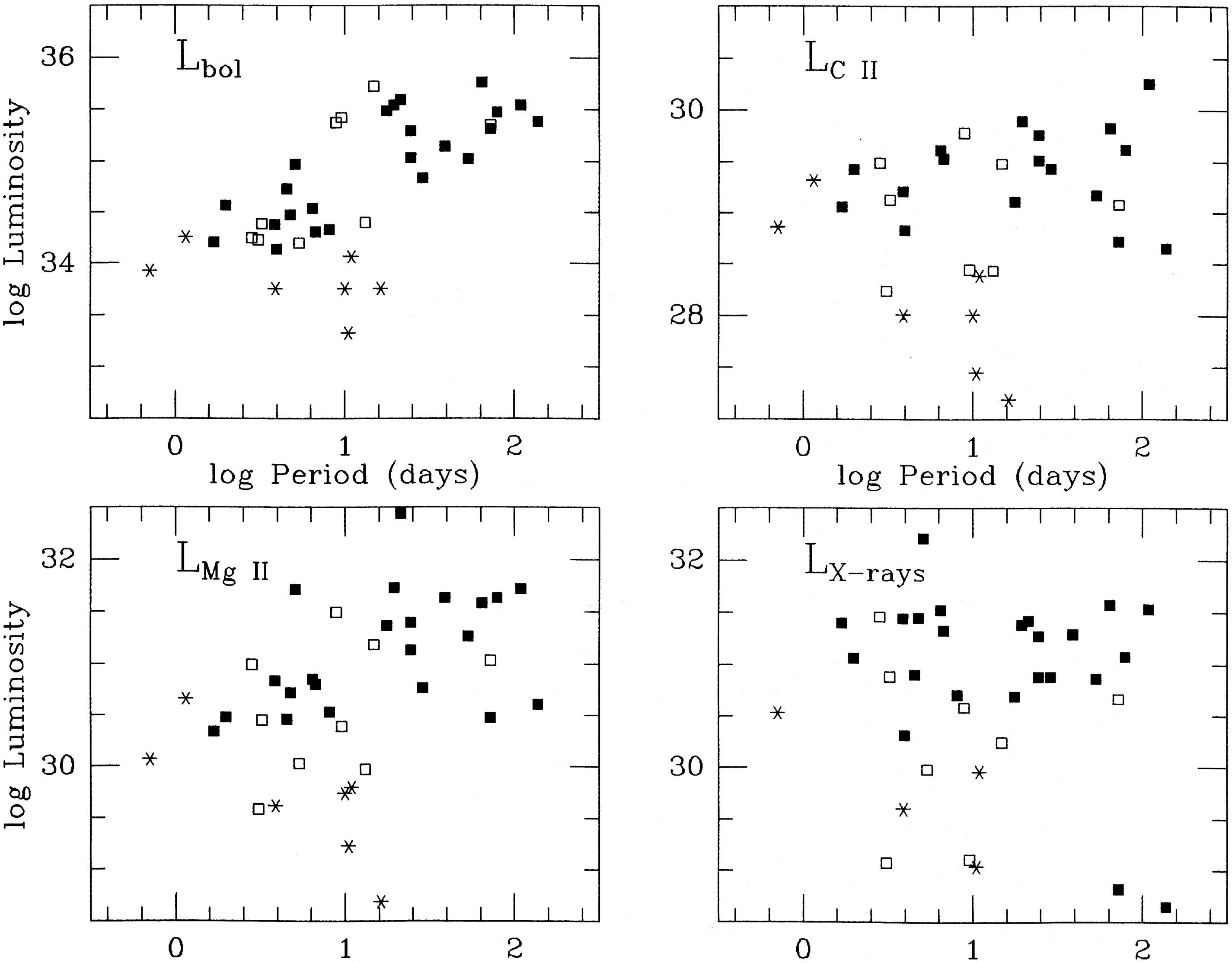


FIG. 1.—Logarithmic relations between total luminosities in various quantities of the active components and rotation period. Filled squares are for systems containing subgiants cooler than spectral type G5; open squares are for hotter subgiants. Asterisks are for systems containing only main-sequence components. Luminosities are for the quantities indicated in each panel, in ergs $s^{-1}$.

for the lower atmospheric layers, and the effect persists even when flux ratios are used (which remove the period-radius dependence). We argue that it is the differences between the bolometric luminosity dependence (which has nothing to do with magnetic fields) and the activity dependences (which presumably do have something to do with them) that are interesting in the context of period-activity relations.

There is a great deal of scatter in the total luminosity relations; this is a reflection of both errors in the stellar parameters and (or the basis of flux ratios below) differences in the filling factors from star to star. There are two stars which appear anomalously low in coronal luminosity, 33 Psc and *o* Dra. Although it is suggestive that 33 Psc has a higher eccentricity than most of the systems, 12 Cam has a similar period and eccentricity with "normal" activity. These two systems are also low in the other activity diagnostics, so they bear further investigation.

### *b) Surface Flux*

The most direct means of studying surface fluxes is to divide the total luminosity by the appropriate area. We have used areas for only the active stars in this study. For some systems it is not known whether both stars are active or not, so we make a guess based on similar spectral types, but there could be surprises, as for Capella (Ayres, Schiffer, and Linsky 1983) or HR 1099 (Simon and Linsky 1980). The period–surface flux relations are shown in Figure 2; these are quite striking for all diagnostics. The upper left-hand panel of Figure 2 shows bolometric surface flux, which is really just an expression of effective temperature. This shows a small tendency for the larger stars to be cooler and demonstrates that, when bolometric surface flux is plotted with the same dynamic range as typical activity diagnostics, there is relatively little scatter in total stellar output.

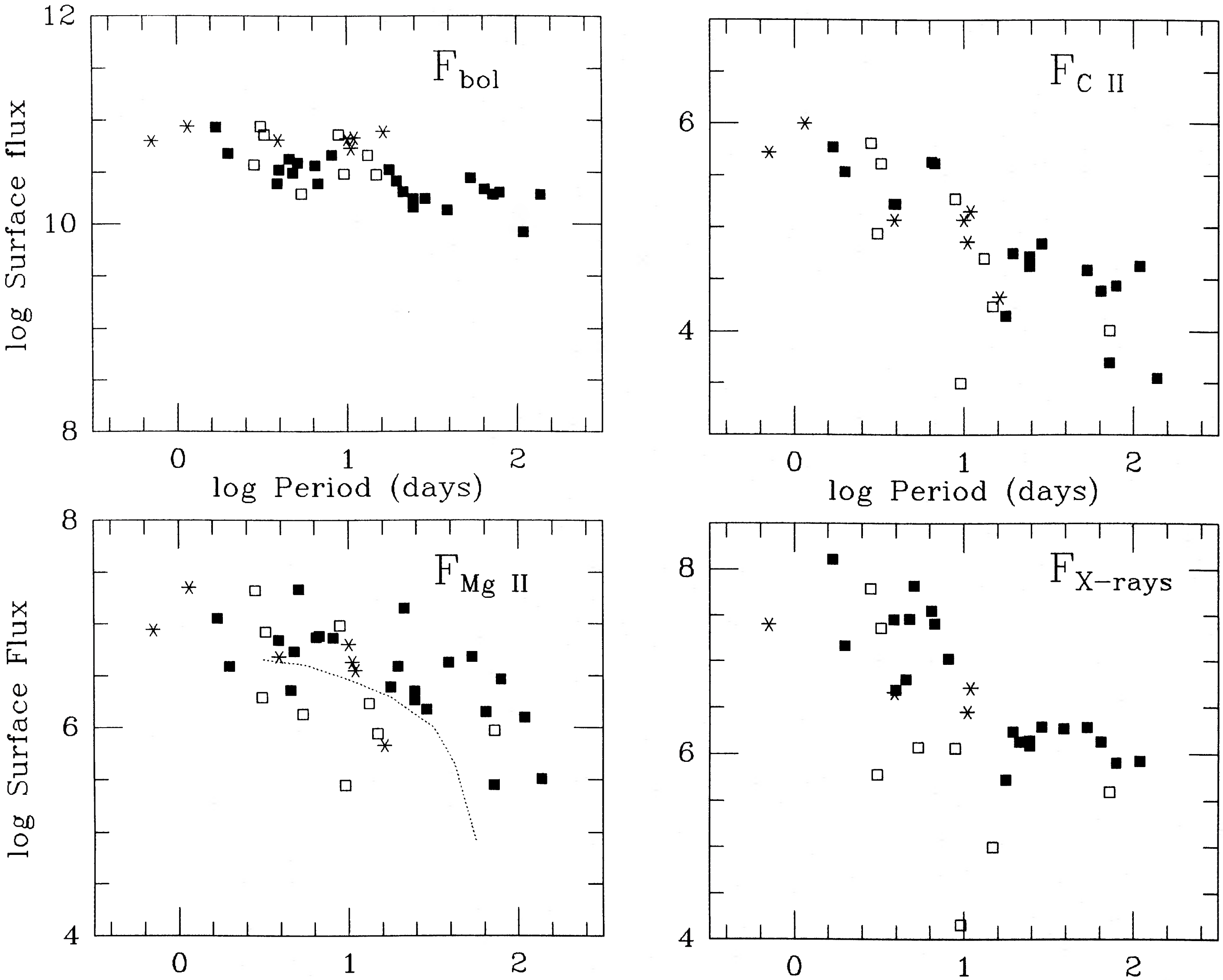


FIG. 2.—Logarithmic relations between surface fluxes and rotation period. Symbols are as in Fig. 1. The surface fluxes are found by dividing the total luminosities by the areas of the active components, and are in ergs $s^{-1}$ $cm^{-2}$. The dotted line in the lower left-hand panel corresponds to an approximate upper limit for single stars from the data of Hartmann *et al.* (1984).

The activity diagnostics all show a decrease with increasing period, as seen in Table 3, least pronounced in the chromosphere and most pronounced in the corona. Neutral oxygen actually shows nearly the same dependence as bolometric flux, indicating that there is little justification for deducing a dynamo-related dependence for this diagnostic. It is possible that Bowen fluorescence plays a role for this line, especially in the more luminous stars (Haisch *et al.* 1977). There is some ordering of slope with expected height (or temperature) of formation, with Mg II, C II, C IV, and X-rays behaving according to expectations. Si IV and He II have shallower slopes than might be expected, and N V is particularly anomalous (appearing similar to Mg II). We argue below that the 1240 Å feature is significantly contaminated by chromospheric blends; He II may also be contaminated to a significant extent.

One might argue that the period dependence is induced by the period-radius relation. As with total luminosity, this would not explain the different slopes for different diagnostics. This is not to say that there is no effect. In fact the magnitude of the slopes is certainly increased by the period-radius relation, by about $-0.33$ judging from the bolometric flux. These relations are also subject to the full uncertainties in stellar parameters.

Before moving on, it is very instructive to examine the Mg II relation in more detail, because the most extensive comparison with single dwarfs can be made here. Shown in the lower left-hand panel of Figure 2 is a dotted line approximating the upper bound of an identical figure from Hartmann *et al.* (1984) for Mg II in single stars. Note that the differences in radii have been removed by considering surface flux. The dwarfs and hotter subgiants in our sample are marginally consistent with the results of Hartmann *et al.* The upper bound for the RS CVn stars has a very similar shape and lies about an order of magnitude above the single stars. This could be construed to support the hypothesis of Young and Koniges (1977) that binarity plays a role beyond that of controlling rotation rates, but an alternative interpretation is that the changing internal structure of the evolving stars is the reason for increased activity. In any case, it appears that the synchronized binaries with cool subgiants are more active in all senses than single dwarfs with the same rotation period. As discussed in § IV, this must be tempered by the results using rotation velocity instead of period.

The results for N V are rather surprising in that this is a high-temperature diagnostic formed above C IV in the transition region, yet its behavior is that of a chromospheric line. It does tend to be both relatively weak and sometimes placed on the wing of the geocoronal Lyman-alpha feature, both of which imply greater errors in our measured fluxes. On the other hand, the line is stronger in this sample of stars than for most late-type stars studied by *IUE*. Closer examination of the feature shows that it does not always appear at exactly the right wavelength, or shows a possible double-peaked appearance. One explanation for our results could be that there is a blending problem, and that chromospheric lines are contaminating the measurement of N V. Possible candidates include C I $\lambda\lambda$1241.3–1246.2, S I and Fe II $\lambda$1241.9, and N I $\lambda$1243.2. If these are the cause of the surprisingly low slope, it means that all N V results obtained on cool stars in the SWP low-dispersion mode are suspect. We are cautiously tempted to discount our results for the 1240 Å feature.

Another approach to surface fluxes is by normalization with the bolometric luminosity. This often-used quantity, $R$, provides a measure of the fraction of the total energy flux which appears as nonradiative heating, and avoids the uncertainties of stellar distance and radius. It differs from the surface flux above in that lower temperature stars are raised at a given radius. The period-activity relations for this quantity are similar to that for the surface flux above, with slopes about 0.3 less, owing to the fact that the long-period systems are cooler. Surprisingly, the scatter is actually a little greater, despite the absence of some of the possible errors in radius and distance. This implies that effective temperature has even less to do with activity levels per unit surface area than does the stellar radius, so that additional scatter is introduced by considering $R$ instead of $F$. A similar effect is apparent in the data of Noyes *et al.* (1984) and Hartmann *et al.* (1984); it is possible that $R$ is not as fundamental a parameter as it first appears. This is not too surprising, since the energy source for the activity is derived from the convection zone, rather than directly from the thermonuclear burning giving rise to $L_{\rm bol}$. It is clear from the photometric waves observed on many of these stars that there can be intermediate storage and release of observable fractions of the total stellar output, perhaps in that case because of magnetic spotting activity. This implies that the total stellar energy release and the energy available for stellar activity are only loosely connected, in which case normalization by bolometric luminosity has no strong physical meaning. Unfortunately, taking the other approach of modifying the period by a Rossby number seems to us to be difficult because of the rather uncertain evolutionary status of each subgiant in our sample.

We recover the Walter and Bowyer (1981) result of a linear dependence of $l_x/l_{\rm bol}$ on period, but note that the slope of the relation of actual X-ray surface flux to period is 1.3, with slightly less scatter. It is clear that interpretation of any of these slopes with dynamo theory must await inclusion of some understanding of what the best measure of "activity" really is in that context, and almost certainly a better knowledge of the filling factors. This latter problem can be properly attacked when high-dispersion UV, EUV, and X-ray spectroscopy provides good loop density distributions. At the moment there is one means of removing the basic uncertainty: using a judiciously selected flux ratio.

### *c) Activity Flux Ratios*

The most unambiguous rotation-activity relations can be found by using flux ratios normalized by an activity diagnostic which can be expected to cover approximately the same surface area as the other diagnostics, in addition to removing all dependence on knowledge of stellar parameters. Of course, if the normalizing flux itself has a dependence on period, all slopes found will be reduced by that amount. From the previous analysis we have a good idea of the size of that effect. It is well known that the various activity diagnostics are correlated with one another (Ayres, Marstad, and Linsky 1981; Orange, Zwaan, and Middlekoop 1982). This does not guarantee rotation-activity relations, however, since if there were perfect correlations between diagnostics with no dependence on rotation, one would obtain scatter diagrams with no slope as a function of period for all diagnostics. We chose to use Mg II as the normalizing flux because it was known for all but one of our sample; judging from the results above, we know that the slopes found will be 0.15–0.2 less than if Mg II itself had no dependence on rotation (as is clearly seen from the O I/Mg II relation).

Shown in Figure 3 are some of the rotation-activity relations found. They exhibit significantly less scatter than for other ordinates. For example, $\delta$ Tri, which is anomalously low in C II surface flux (Fig. 2, *upper right-hand panel*) is not out of place in the upper right-hand panel of Figure 3, probably indicating that this star has a rather low filling factor. The scatter could probably be reduced even further, especially for the corona, by using Mg II enhanced by the appropriate correlation slope for each diagnostic. There is a clear dependence on rotation, in agreement with the more ambiguous results above. The small positive slope of the relation for O I is a sure sign that Mg II has some dependence on rotation, with a slope of roughly $-0.2$. The diagnostics with slopes similar to Mg II are C I, N V (+C I), Si II, Si IV, and He II (+Fe II). C II and C IV are very similar to each other and 0.2 steeper, and X-rays are 0.75 steeper. Thus there appears to be a relatively good ordering of increasing slope with temperature of formation, the only unambiguous exception being Si IV.

The important conclusion of this work is that there is a definite dependence of activity on rotation; the fact that the rotation-activity relations have steepening slopes for hotter diagnostics had already been expected from the known correlation slopes among the diagnostics. The rotation connection is made clearer by the steepness of the slopes for the hotter diagnostics, but is undeniably present for all diagnostics except O I. Since the Mg II flux ratio has removed the effects of both differing stellar radii and differing filling factors, we can now confidently state that *there is an intrinsic dependence of activity on rotation for the synchronized binaries*. This fact allowed us to argue in earlier sections to what extent the relations there were influenced by the dependence of stellar parameters on orbital period. As it happens, after allowing for the intrinsic slope of Mg II, we recover the linear dependence of coronal activity on rotation of Walter and Bowyer (1981). This may now be interpreted as a localized effect (per unit active surface area). The use of rotation velocity instead of period makes little difference for our sample, as can be seen from Table 3. At periods shorter

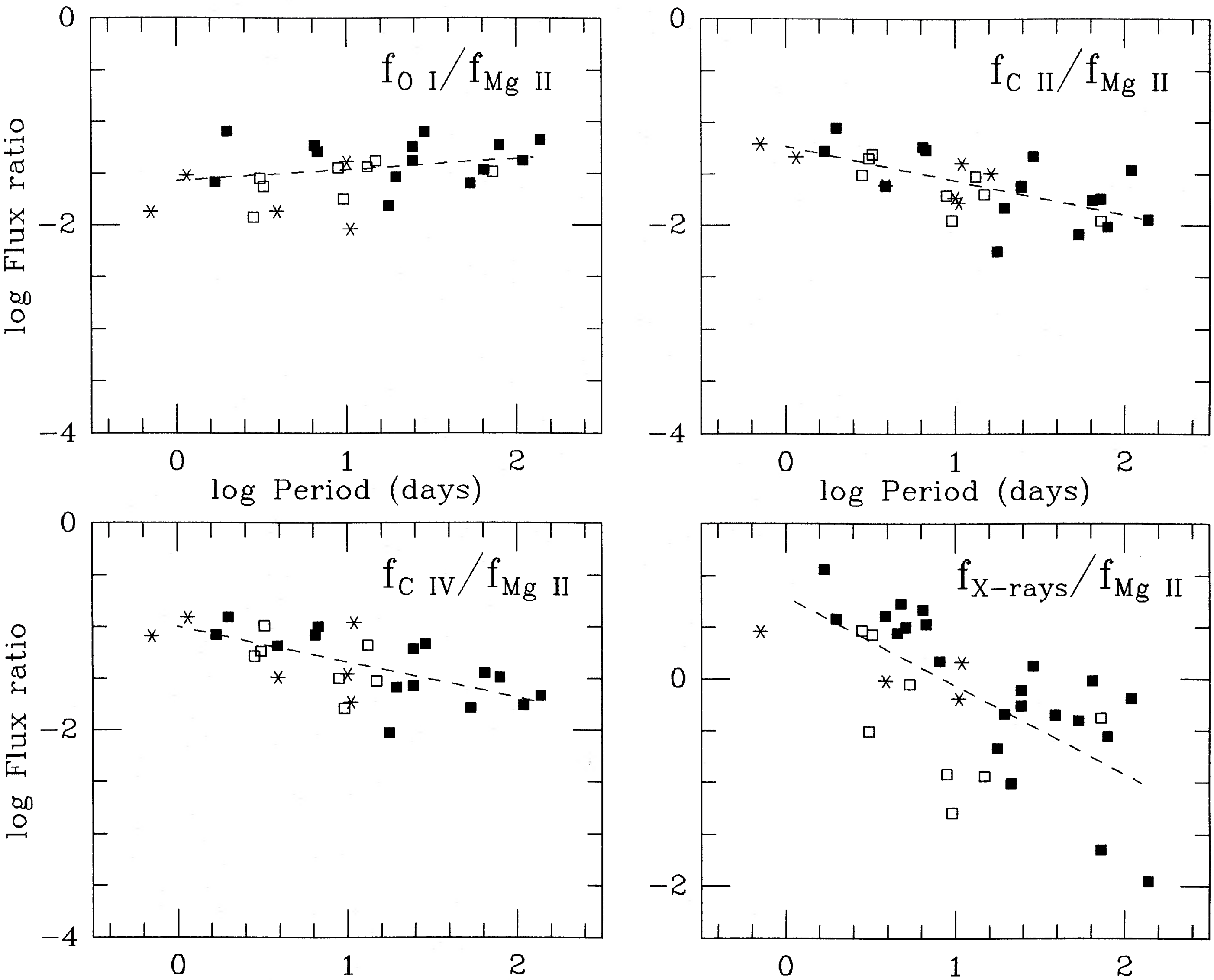


FIG. 3.—Logarithmic relations between the flux ratios (at the Earth) indicated in each panel and the rotation period. Normalization by Mg II flux eliminates uncertainties in the stellar parameters and reduces ambiguites due to differing filling factors of activity. Dashed lines are least-squares fits as given in Table 3.

than 1 day, the correlation with rotation apparently changes sign, as discussed by Vilhu and Ruciński (1983).

## IV. DISCUSSION AND SUMMARY

The subject of rotation-activity relations in the synchronized binaries is complicated by a dependence of stellar parameters on orbital period that is unrelated to questions of stellar activity. We have disentangled the two effects by considering several ways of looking at such relations. We find an intrinsic dependence of activity on rotation when considered as surface flux, and find that this dependence becomes stronger as one moves from the chromosphere to the corona. This latter effect is quite consistent with the known steepening of the correlation slopes among the activity diagnostics (without considering rotation). The combination of these effects leads to an apparent lack of rotation-activity dependence for total coronal luminosity, since the larger area of the long-period stars is compensated by their weaker surface fluxes. One increasingly sees slopes which approach the dependence of bolometric luminosity on orbital period as one moves down to the chromospheric diagnostics. We therefore do not ascribe any striking significance to the lack of rotation-activity dependence in total coronal luminosity. For all the diagnostics there is a great deal of scatter in the total luminosity; this is not too surprising considering the range in size and spectral type of our sample.

We have considered three different representations of surface flux. The method yielding significantly smaller scatter involves a removal of the filling factor variation by normalization with Mg II. We find that the power-law coefficient relating Mg II surface flux with period is around −0.2, after removal of unrelated correlations of stellar parameters with rotation. This is significantly less than the dependence initially expected from Ca II results on single stars (e.g., Middlekoop 1981), but is apparently consistent with both Mg II results for single stars (Hartmann *et al.* 1984) and some work with Ca II on these binaries (Bopp 1984). Neutral oxygen apparently has no dependence on rotation, perhaps because the more luminous stars are more subject to Lyman-beta pumping of these lines.

After accounting for the intrinsic dependence of Mg II on rotation (as deduced from the other two methods), C II and C IV have coefficients close to $-0.5$, and the coronal surface flux is close to the previously reported value of $-1$. The behavior of the other transition region lines is more similar to the chromospheric behavior; we argue for some of these lines that blending with lower temperature lines may be a partial explanation, but this is somewhat unsatisfactory. Ionized helium decidedly does not show the coronal dependence predicted by Hartmann, Dupree, and Raymond (1982); again, blending is a possible explanation.

Consideration of the surface fluxes themselves (unnormalized by a flux ratio) yields stronger dependences because of the period-radius dependence in these systems. The scatter in these relations is less than one might expect given the intrinsic uncertainties in stellar parameters. The period-radius relation itself adds about 0.33 to the magnitude of the slopes. Normalization of the total luminosity by bolometric flux to give a fractional surface flux weakens those dependences as a result of the tendency of the long-period systems to be cooler, and introduces some additional scatter. Thus $R_{hk}$, for example, is rather scattered and not obviously dependent on rotation for these stars. We make some arguments that there is not a good physical reason for considering this normalization to yield a fundamental measurement. Use of any particular set of rotation-activity relations for these stars to compare with dynamo theories must therefore be explicitly motivated by prediction of the same set of variables from the theory.

The results using velocity instead of period tell basically the same story at first glance, though with slightly larger scatter. There is an intrinsic correlation in this sample between velocity and period through the larger radii of longer period systems, which tends to minimize the velocity range. Closer inspection does not really resolve whether period or velocity is the more fundamental variable. The binary dwarfs have a tendency to increase the scatter and flatten the slope of velocity–surface flux relations but not period–surface flux relations. This is because the moderate-period dwarfs are bright but rotate with slower velocities than subgiants at that period. This could be considered weak evidence in favor of period.

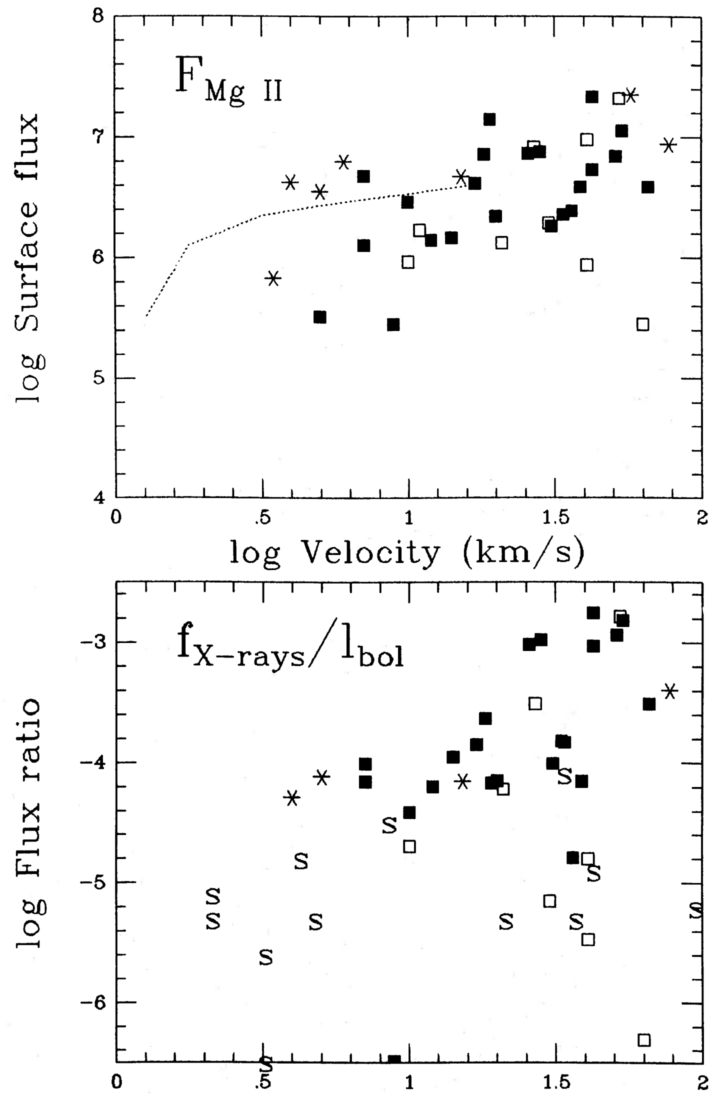


FIG. 4.—Two comparisons of the binaries with single stars using surface rotation velocity instead of period as the abscissa. *Upper panel:* Surface flux in Mg II versus velocity. The dotted line is as the lower left-hand panel in Fig. 2, where we have converted periods to velocity using canonical assumed radii. *Lower panel:* $R_x$ versus velocity. The *S* symbols are single stars derived from data in Pallavicini *et al.* (1981). Those at the lower right are F stars.

On the other hand, the upper panel in Figure 4 shows that in our best comparison of binaries and single stars, Mg II surface fluxes, the use of velocity instead of period tends to reduce the distinctions between all the stars at velocities they have in common. The line in this figure is again a representation of the upper bound of the Hartmann *et al.* (1984) data, with radii of 0.8–1.2 assumed for the stars in their sample according to $B-V$. On average the dwarfs have lower velocities relative to subgiants of the same period, placing them among binaries with similar surface fluxes.

Another comparison with single stars can be made for the corona, using data from Pallavicini *et al.* (1981). Apart from the F stars at the lower right in the lower panel of Figure 4, the single dwarfs (represented by $S$) are not inconsistent with the binaries when $l_x/l_{\mathrm{bol}}$ is considered. Most of these are to the right of their true position because of the unknown inclinations. We have excluded the dMe stars, which are very bright in this measure. There is no strong reason from these comparisons to prefer either velocity or period as the abscissa.

In summary, we can state the following conclusions, which become less firm as the list progresses: (1) There is a dependence of activity on rotation in the synchronized binaries; surface flux is the preferable measure of activity and is best when steps are taken to remove variations in activity filling factors. (2) This dependence is approximately linear in the corona and rather weak in the chromosphere (intermediate for the transition region). (3) All activity variations are exaggerated toward the corona by the intrinsic properties of the correlation slopes between activity diagnostics, so the change in rotation-activity slopes probably is not a direct probe of dynamo properties. (4) The synchronized binaries are at most a factor of a few more active (per unit surface area) in the chromosphere compared with appropriate single main-sequence stars. (5) We have found no clear evidence preferring period or surface rotation velocity as the best measure of rotation. (6) It is not clear whether the increased activity in these binaries is due to their evolving internal structures or to tidal coupling, since these tend to occur together. These rotation-activity relations should provide interesting constraints on developing dynamo theories, but they must be applied with care to stars with the same properties as those in our observational sample.

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GIBOR BASRI and ROBERT LAURENT: Astronomy Department, University of California, Berkeley, CA 94720

FREDERICK WALTER: Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309