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STELLAR ACTIVITY IN SYNCHRONIZED BINARIES. II. A CORRELATION ANALYSIS WITH SINGLE STARS

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ABSTRACT

The interdependences between various measures of activity and a number of relevant stellar parameters are explored for a sample of largely post–main-sequence, late-type binaries with orbital periods from one to 100 days. The sample was analyzed for period-activity relations in a previous paper; here I examine the relations between diagnostics formed at various heights in the atmospheres, and between activity and stellar parameters expected to have a bearing on the level of activity. The stars are also compared in detail with single dwarfs having similar periods. I find that the binaries closely resemble the single stars in the way the various activity diagnostics are related to each other. I suggest that activity can be described by a single parameter and that activity structures are similar on all stars.

The primary dependence of activity is confirmed to be on stellar rotation. Tidal coupling is ruled out as a direct factor for increasing activity in binaries. The surface flux is clearly shown to be the preferred means of expressing activity on stars. I suggest that use of the normalized luminosity parameter R for expressing activity is significantly less desirable, and the total luminosity is inappropriate when studying stars in disparate luminosity classes. The binaries and single stars exhibit similar and clear dependences of activity on either their rotation periods or Rossby numbers. There is some evidence that duplicity *per se* is not a strong factor in the activity levels of the binaries. The Rossby number more fully unifies the two samples, while the binaries are more active at a given period than the single dwarfs. Both yield relatively tight relations, however, and there is still no compelling reason for choosing one of these to the exclusion of the other on the basis of the observations.

Subject headings: Ca II emission — stars: binaries — stars: chromospheres

I. INTRODUCTION

The study of stellar activity has received great impetus from the availability of space observations, primarily from the *International Ultraviolet Explorer* (*IUE*) and the *Einstein Observatory*. These data have the advantage that the hot outer atmospheres provide the primary source of flux at short wavelengths for cool stars, and there is automatically a set of homogeneous, calibrated fluxes which can easily be intercompared. A few basic results have emerged from these studies concerning stellar activity. (1) The levels of activity are not primarily fixed by the photospheric condition of a star, or equivalently, by its position in the HR diagram. (2) The primary additional determining parameter for activity levels appears to be the stellar rotation. (3) There is a fairly tight relationship between activity diagnostics at various levels in the atmosphere; activity structures have some coherence from the top of the photosphere into the corona. (4) The structure of the convection zone plays a role in activity levels, in that they start up somewhere near spectral type early F, perhaps diminishing again in the late M stars. These factors come into play in differing fashions for pre–main-sequence evolution, on the main-sequence, and in post–main-sequence evolution. (5) Finally, coronal activity is quenched by the presence of strong mass loss in lower gravity stars.

Beyond these general statements, however, there is a lively discussion about quantitative relations, the best parameters with which to express them, to what extent they are fundamental, and what physical processes underlie them. As the ability to gain new observations rapidly increased, they were made when they became possible rather than in a homogeneous and systematic fashion. There is now enough data that a more systematic analysis is in order. In particular, now that we have some insight as to how to organize samples, we can begin to see how the variation of a particular stellar parameter affects activity while holding other relevant parameters constant. Because it now appears that rotation is a very important parameter, this work contains samples of stars organized by rotation, with other parameters such as evolutionary state, effective temperature, radius, gravity, and convection zone properties also considered. The fundamental question asked is: which of these stellar properties are directly relevant to activity levels or structures and in what way?

The paper is organized as follows: in § II a brief description of the samples and data used is given, § III*a* deals with the correlations among the emission line fluxes, § III*b* deals with the correlations between the line fluxes and stellar parameters, § IV is a critical examination of the role of the Rossby number and further analysis of rotation-activity relations, and § V is a general discussion and summary.

II. OBSERVATIONAL SAMPLE AND DATA

This paper draws largely on two samples of cool stars exhibiting stellar activity, which have in common that their rotation periods are known. The binaries have been chosen because they (almost all) show synchronicity between their orbital periods and rotation periods. Most of them are in systems with nearly unit mass ratio; none are in contact. The periods range from one to 100 days, with spectral types from

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early G to late K dwarfs and subgiants. These stars have been listed and analyzed for period-activity relations by Basri, Laurent, and Walter (1985; hereafter Paper I). Activity diagnostics ranging from the low chromosphere to the corona are available, along with an adopted set of stellar parameters.

The other sample is a set of single main-sequence stars from spectral type F to M for which rotation periods have been determined by the Mount Wilson Ca II photometry program. Measured periods range from two to 60 days. These stars are collected and discussed by Noyes *et al.* (1984) and Hartmann *et al.* (1984). They discuss the results for Ca II and Mg II; both chromospheric diagnostics. I have examined the *IUE* archives and found a large subset of their sample which have short-wavelength camera data also available, often obtained at the same time as the Mg II data. Using the facilities of the Colorado RDAF, I obtained and measured these spectra so that a more extensive comparison between the binaries and single stars could be made, including transition region data. The hotter diagnostics (e.g., C II and C IV) were found in Paper I to be cleaner tracers of the rotation-activity relation in the binaries than Mg II, for example. These stars span essentially the same range in effective temperature and rotation period as the binaries, so many comparisons can be made. The primary differences between the samples are the presence of a tidally locked companion and the preponderance of post–main-sequence status among the binaries. The samples are therefore not fully equivalent, and these differences must be kept in mind when interpreting both similarities and differences in the stellar activity among them.

In order to fully compare the samples, the same stellar parameters have to be available for both sets. The effective temperatures and conversions from observed to surface fluxes were taken from Hartmann *et al.* (1984), but actual radii were derived from the $B-V$ colors and relations in Mihalas and Binney (1981). Line fluxes were measured above the continuum or background levels as has been the usual practice. Noyes *et al.* (1984) have suggested that the Rossby number significantly reduces the observational scatter in their rotation-activity correlations. In order to extend their analysis, one needs Rossby numbers off the main sequence. Fortunately, recent work by Gilliland (1985) fills this need; I have adapted Rossby numbers both on and off the main sequence from his work. A tabulation of the adopted stellar parameters and surface fluxes used in the analysis for the single stars appears in Table 1. The observed fluxes in other short wavelength lines of interest for these stars are given in Table 2.

Another parameter which has been suggested by Young and Koniges (1977) as relevant to the activity levels in the binaries is the tidal coupling, expressed as the ratio of the stellar to the Roche radius. The radii of the evolving binaries are rather poorly determined, except in eclipsing systems. An attempt to obtain consistent radii was made in Paper I, using previous observational determinations where possible. The other quantity required is the stellar mass. This is also poorly determined for most systems, although there are a few firm determinations from the eclipsing systems. I have tried to make reasonable estimates for the others, based on the spectral type of main-sequence components where they were present, or a comparison to similar systems with better determinations in a few cases. Most systems for which the mass ratio is known show almost equal masses; for simplicity I have assumed both unit mass ratio and circular orbits for all the systems. In this case, the Roche radius can be approximated by $R_{\rm Roche} \approx 5/3 M_*^{1/3} P^{2/3}$. The units are solar radii and masses and the period is in days. The stellar parameters presented here should not be taken too seriously but should suffice to discover whether a correlation with activity is plausible or not. Masses are likely to be lower limits; while the radii cannot be too different from the estimates without becoming inconsistent with the luminosities and effective temperatures adopted. The binary sample employed here is a large subset of those from Paper I; a few were dropped because of the incompleteness of observations. In Table 3 the sample appears along with the estimated stellar parameters not given in Paper I.

TABLE 1

SINGLE STARS

Star (HD)	$T_{\rm eff}$ (K)	R ($R_\odot$)	log P (days)	log R_0	log $F_{\rm Mg\,II}$	log $F_{\rm C\,II}$	log $L_{\rm bol}$
Sun	5754	0.96	1.40	−0.03	6.10	3.83	33.57
1835	5623	0.96	0.88	−0.54	6.44	4.63	33.53
16673	6095	1.11	0.76	−0.43	6.28	4.77	33.67
17925	5099	0.84	0.82	−0.71	6.28	4.62	33.36
20630	5559	0.94	0.96	−0.49	6.47	4.51	33.51
22049	5070	0.84	1.05	−0.48	6.27	4.43	33.35
30495	5656	0.98	0.88	−0.54	6.50	4.47	33.54
39587	5888	1.04	0.72	−0.58	6.59	4.80	33.61
82885	5339	0.88	1.26	−0.22	6.11	4.39	33.44
97334	5821	1.01	0.88	−0.50	6.48	4.68	33.59
101501	5464	0.90	1.23	−0.22	6.33	4.43	33.48
114710	5922	1.05	1.09	−0.21	6.03	4.44	33.62
124850	6131	1.12	0.88	−0.12	6.40	4.61	33.68
131156	5370	0.88	0.79	−0.69	6.38	4.73	33.45
149661	5248	0.87	1.33	−0.17	6.15	4.30	33.41
155886	5129	0.85	1.31	−0.22	6.21	4.41	33.37
160346	4870	0.81	1.53	−0.05	5.89	4.14	33.28
165341	5129	0.85	1.29	−0.24	6.20	4.41	33.37
201091	4315	0.74	1.58	−0.15	5.71	3.70	33.07
201092	3802	0.65	1.68	−0.14	5.47	3.49	32.85
206860	5922	1.05	0.66	−0.64	6.57	4.86	33.62

NOTE.—$F_{\rm Mg\,II}$, $F_{\rm C\,II}$ in ergs cm^{-2} s^{-1}; $L_{\rm bol}$ in ergs s^{-1}.

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TABLE 2

OBSERVED FLUXES FOR SINGLE STARS

Star (HD)	$\log f_{O\,I}$	$f_{C\,IV}$	$f_{C\,I}$	$f_{Si\,II}$	$f_{He\,II}$	$f_{N\,V}$
Sun	5.60	6.60	8.40	24.00	3.60	0.90
1835	4.05	9.60	15.30	17.20	5.90	2.50
16673	4.96	5.20	10.00	...	...	...
17925	12.70	23.70	22.80	29.70	15.70	3.60
20630	19.60	42.30	31.80	76.90	22.70	6.10
22049	70.95	94.20	77.80	174.20	54.50	17.90
30495	9.40	15.70	14.20	28.50	14.10	8.60
39587	34.40	66.70	71.90	107.60	13.20	11.00
82885	14.50	14.60	10.30	29.50	17.10	14.50
97334	2.90	7.60	10.20	...	3.30	1.80
101501	7.80	20.00	26.50	22.90	5.20	...
114710	16.70	27.10	21.20	...	5.40	6.40
124850	35.00	71.80	13.10	...	16.60	9.75
131156	26.00	53.00	63.00	117.00	46.00	23.00
149661	5.10	11.80	12.60	24.10	3.75	2.60
155886	33.20	40.00	113.00	...	15.70	49.00
160346	1.50	1.40	2.80	7.50	...	1.50
165341	36.90	62.60	56.80	115.00	31.20	8.90
201091	11.30	11.40	17.70	34.40	8.50	4.90
201092	5.70	14.90	...	17.30	...	4.70
206860	7.60	13.55	18.70	64.00	8.30	6.40

NOTE.—All fluxes are in units of 10^{-14} ergs cm^{-2} s^{-1} observed at the Earth.

TABLE 3

CLOSE BINARIES

Star	T_{eff}^{a} (K)	R[a] ($R_\odot$)	Mass[a] ($M_\odot$)	log P (days)	log R_0	log $F_{Mg\,II}$	log $F_{C\,II}$	log L_{bol}	R_*/R_{Roche}
HD 155555	5000	1.8	0.50	0.23	−1.55	7.05	5.77	34.20	0.95
AR Lac	4700	3.6	1.35	0.30	−1.66	6.59	5.53	34.57	0.89
Sz Psc	4600	4.0	1.70	0.59	−1.29	6.84	5.22	34.38	0.79
Z Her	4700	2.6	1.10	0.60	−1.36	6.85	5.22	34.14	0.60
UX Ari	4700	3.9	0.70	0.81	−1.15	6.87	5.63	34.54	0.65
II Peg	4600	3.7	>1.00	0.83	−1.03	6.88	5.61	34.31	0.63
ζ And	4400	12.4	2.70	1.25	−0.36	6.39	4.15	35.48	0.81
σ Gem	4600	15.0	>1.00	1.29	−0.57	6.59	4.75	35.54	0.98
HK Lac	4800	14.9	>1.40	1.39	−0.52	6.26	4.63	35.29	0.95
HR 8703	4200	10.0	>1.25	1.39	0.08	6.35	4.72	35.03	0.65
HR 7275	4700	8.0	>2.60	1.46	−0.50	6.17	4.84	34.83	0.37
λ And	4700	7.9	>1.00	1.73	−0.74	6.68	4.59	35.02	0.32
HR 4665	4400	21.1	1.75	1.81	−0.26	6.15	4.39	35.76	0.36
33 Psc	4700	13.2	>1.80	1.86	−0.61	5.45	3.70	35.31	0.49
12 Cam	4700	15.6	>1.10	1.90	−0.57	6.46	4.44	35.47	0.35
HR 7028	5000	26.0	>1.60	2.04	−0.23	6.10	4.63	35.54	0.22
ο Dra	4300	14.3	>2.50	2.14	0.17	5.51	3.55	35.38	0.83
HR 1099	5100	2.8	1.20	0.45	−1.77	7.32	5.81	34.25	0.35
TY Pyx	5600	2.35	1.20	0.51	−1.51	6.92	5.61	34.39	0.45
α Aur	5100	7.3	2.50	0.95	−1.27	6.98	5.27	35.37	0.74
1 Gem	4800	12.0	>1.90	0.98	−1.44	5.45	3.50	35.42	0.98
42 Cap	5400	3.0	>1.00	1.12	−0.97	6.23	4.70	34.40	0.32
6 Tri	5300	17.0	>1.10	1.17	−0.95	5.94	4.24	35.72	0.98
93 Leo	5300	13.8	>2.00	1.86	−0.26	5.97	4.01	35.35	0.39
θ Dra	6200	1.8	>1.20	0.49	−0.78	6.29	4.94	34.23	0.49
ξ Boo	5600	0.8	>1.10	1.02	−1.00	6.63	4.86	33.33	...
ER Vul	5600	1.5	1.00	−0.15	−1.87	6.94	5.72	33.93	0.81
σ CrB	6300	1.8	>1.20	0.06	−1.11	7.35	6.00	34.26	0.68
ξ UMa	5900	1.2	>1.10	0.59	−1.23	6.68	5.07	33.76	0.28
δ Tri	5900	1.2	>1.30	1.00	−0.82	6.80	5.07	33.76	0.14
54 Cam	5900	1.70	1.6	1.04	−0.78	6.55	5.15	34.07	0.11
16 UMa	6000	1.10	>1.2	1.21	−0.46	5.83	4.33	33.76	0.10

NOTE.—$F_{Mg\,II}$ in ergs cm^{-2} s^{-1}; L_{bol} in ergs s^{-1}.

[a] Weighted average if two active components.

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III. CORRELATION ANALYSIS

a) *Activity Diagnostics*

It has been known for some time that there are very good correlations between the activity diagnostics formed at different heights or temperatures in the active stellar atmosphere. Since the work of Ayres, Marstad, and Linsky (1981), observers have found tight correlations with similar slopes between emission line fluxes from the chromosphere (Ca II, Mg II, Si II), transition region (C II, C IV, Si IV), and the corona. The slopes of these power-law relations are generally found to steepen when hotter diagnostics are plotted against cooler diagnostics, with the greatest slope occurring in soft X-rays relative to low chromospheric diagnostics. These results have been confirmed by the work of Orange, Zwaan, and Middlekoop (1982), Marilli and Catalano (1984), and several other authors. The stars used in those analyses generally include a variety of spectral types and luminosities. Even so, the correlations are remarkably good power laws, among the tightest found in the study of stellar activity. The samples studied here are no exception. Correlations between the diagnostics are at the 0.8–0.9 level when logarithmic surface fluxes are considered.

Comparison of the dwarfs with the subgiants allows examination of the effect of stellar surface gravity. In Figure 1 are displayed the variations of diagnostics relative to C II. This line is chosen because it showed the clearest rotation-activity relation for the binaries, more data is available for it than other hot diagnostics, it is relatively unblended and strong, and it yields essentially the same information as C IV (which is sometimes unavailable because of the rapidly rising early-type companion continuum for some of the binary systems). The meanings of symbols in all the figures are as follows: squares are binaries, triangles are single stars, filled symbols are on the main sequence. In Figure 1*a* Mg II has a power law with slope 0.7 with respect to C II and a scatter of about half an order of magnitude about this. The single stars mix well with the binaries at the same activity levels, and there is no evidence of different slopes for the two samples. The implication is that activity structures scale similarly for all these stars. The slope found is consistent with the earlier results, confirming a very universal relation between the chromosphere and corona for all stars which don't exhibit strong mass loss. Figure 1*b* shows that an even tighter relation exists between two diagnostics both thought to belong to the transition region (although formed at different temperatures). There is a slope of 1.15 for the power-law relation between C II and C IV. This agrees with the general trend noted by earlier authors that the slope steepens as higher temperature lines are considered (with the abscissa kept the same). Results for the other diagnostics are consistent with this. The only diagnostic which apparently shows an effect of gravity is O I. In Figure 1*c* the subgiants lie generally higher than the dwarfs at given C II levels and show a shallower slope. The subgiant slope is close to the Mg II result, while the single stars have slope 0.85. We may be seeing the gravity-dependent effects of Bowen fluorescence as suggested by Haisch *et al.* (1977).

These correlations are so pervasive and convincing that (*a*) they must be taken as strong evidence that activity structures are similar across a wide variety of stellar parameters and (*b*) they are more fundamental than variations of particular diagnostics with stellar age, rotation, or other relevant parameters. Thus for example, the variation of rotation-activity slopes with various diagnostics found in Paper I should be regarded as a single dependence of "activity" on rotation, modulo the interdependences of the diagnostics on each other. Likewise, the various dependences of diagnostics on age found by Simon, Herbig, and Boesgaard (1985) may be viewed in a similar light. This has the helpful implication that it is not necessary to study "activity" in all the various diagnostics available to gain fundamental knowledge of its dependences on relevant param-

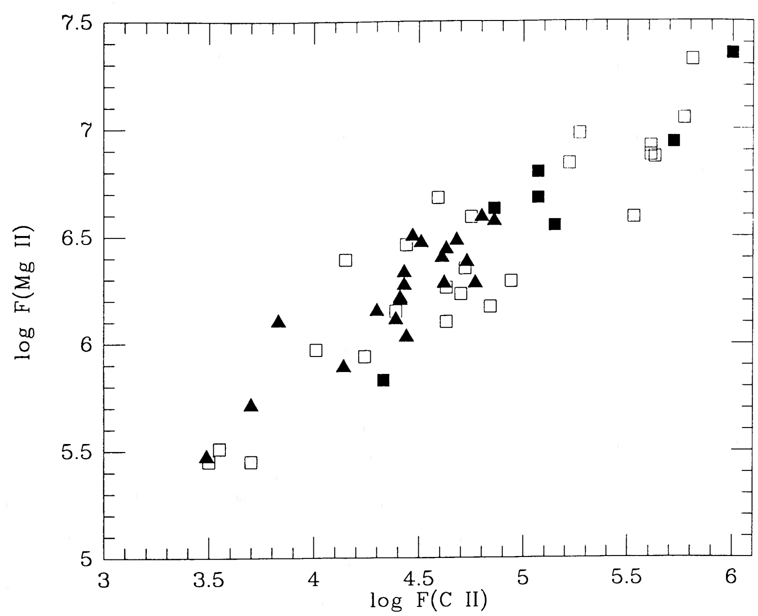

FIG. 1*a*

FIG. 1.—The correlations between different activity diagnostics. Surface fluxes in ergs s^{-1} cm^{-2} are shown, with C II as the abscissa because it is the diagnostic which is both most unblended and has good dynamic range. *Squares:* close binary systems. *Triangles:* single stars. *Filled symbols:* stars on or very near the main sequence. Note that only for O I does there seem to be a difference between the evolved binaries and the single dwarfs.

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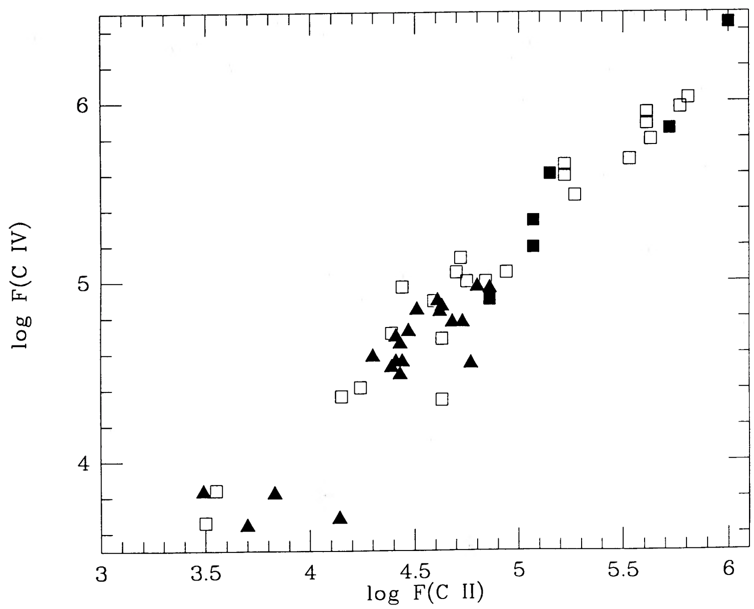

FIG. 1*b*

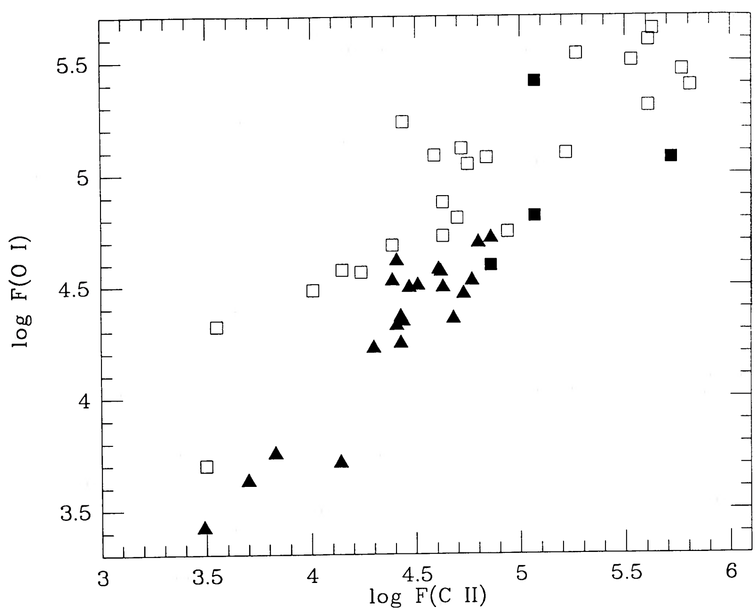

FIG. 1*c*

eters; one or two relations in observationally convenient lines can be generalized.

It has been suggested (Hartmann, Dupree, and Raymond 1982) that there is a particularly strong and physically significant correlation between the He II λ1640 emission flux and the coronal soft X-ray fluxes in cool stars. This could arise if the He II emission has recombination from X-ray photoionization as its primary production mechanism. It would be important because it affords a means of measuring coronal fluxes without the necessity of X-ray observations. The binary sample here affords a good means of testing this hypothesis, since both He II and X-ray fluxes are available for most of the stars. In Figure 2 the He II and C II fluxes as a function of X-ray flux in the binaries are shown (the X-ray coverage of the single star sample is much less complete). Basri and Laurent (1983) had earlier reported that the correlation coefficient was highest for He II compared with the other diagnostics relative to X-rays. This remains true (the data here is largely the same), but there is no strong evidence that the behavior of He II is different from other transition region diagnostics. The difference in correlation coefficients could arise from the smaller sample of He II fluxes used and is not really statistically significant. A further prediction of the X-ray recombination model is that the correlation *slope* be closer to unity for He II than for other diagnostics with respect to X-rays; this is clearly not the case. Unfortunately, it is likely that at the low resolution of all these *IUE* observations there is blending of Fe II and other emission in the 1640 Å feature. A final determination of whether He II can serve as a proxy diagnostic of coronal fluxes must therefore await Space Telescope HRS observations.

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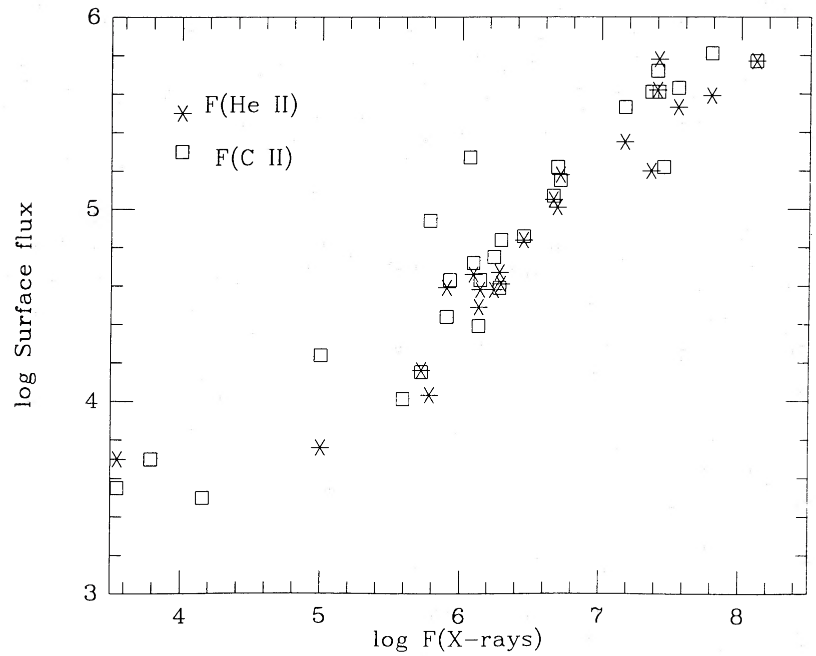

FIG. 2.—A comparison of the correlation of C II surface fluxes (*squares*) and He II fluxes (*asterisks*) with X-ray fluxes for the close binaries. There is little evidence that He II is more closely correlated with coronal fluxes than other transition region diagnostics.

b) Stellar Parameters

Of fundamental interest is the question of which stellar parameters are responsible for determining the level of activity. A related question is what measure of activity best elucidates these correlations; it would be interesting to know, for example, whether to study activity on the local (individual flux tube) level or be concerned more with the total nonradiative output of a star. Both are of intrinsic interest, but one may be more closely related to the root causes of stellar activity. I study three measures of activity here: F_a, the surface flux in a particular emission line a; R_a, the luminosity in line a divided by the bolometric luminosity of the star; and L_a, the unnormalized luminosity in a line (total emission). Two measures of rotation were originally considered, the linear surface velocity and the surface angular velocity. In main-sequence stars these are almost equivalent because the radii are similar. Their differences in rotation-activity relations for the binaries (which have a wide range of radii) were discussed in Paper I. For the purposes of this section (to look at correlations rather than relations) they are not significantly different; I use the angular velocity. An additional parameter considered here which is related to rotation is the Rossby number R_0. This has been suggested (see § IV) as a means of including both rotation and convection information which might be relevant to dynamo activity and so is theoretically more compelling.

I study the correlations of these with fundamental stellar parameters, namely, the bolometric luminosity $L_{\rm bol}$, the effective temperature $T_{\rm eff}$, and the stellar radius R_*. An additional parameter of possible interest in the synchronized binaries was suggested by Young and Koniges (1977) as a possible agent for the elevated activity in binaries, namely, the ratio of stellar radius to Roche radius. This presumably characterizes the tidal stresses near the surface of the star, which they felt might be directly responsible for increasing the stellar activity. The (rough) determination of this parameter for the systems here was discussed in § II.

The "activity" used here is an average over chromospheric, transition region, and coronal diagnostics. I have examined the separate correlations for Mg II, C II, O I, C IV, Si II, He II, and X-rays but have tried to abstract the general results rather than list innumerable details. One persistent trend is that in the binaries (the coronal data is lacking for this main-sequence sample), the correlations are weaker in X-rays than in the other diagnostics. A graphical representation of the general correlations appears in Figure 3. The fuller a square, the better the correlation. An empty square means a correlation coefficient less than 0.2, a half full square means a correlation coefficient of 0.4–0.6, and a full square means a correlation coefficient greater than 0.8. There are separate diagrams for the binaries and the single dwarfs. Sometimes correlations among samples this small can be driven by a few individuals; I have examined the correlation plots to help guard against this. Nonetheless, the results should be taken as only indicative until much larger samples are available.

Several interesting points are apparent in Figure 3. First, the main-sequence stars are not a very demanding sample on which to test for correlations. They are rather similar to each other in both the contexts of fundamental stellar parameters and stellar activity. Indeed, there are only two areas where high correlations are not observed. One is between the Rossby number and the individual fundamental stellar parameters. This is partly due to the fact that a slowly rotating cool star has a Rossby number similar to a rapidly rotating hot star. It is also partly due to the fact that while the stellar properties themselves change very little while the star is on the main sequence, the Rossby number does change due to the spindown of the star. The stellar parameters are also poorly correlated with the normalized activity flux R_a. Much has been made of this lack of correlation in the literature (e.g., Basri and Linsky 1979); it has been the main evidence that stellar activity does not depend on location in the HR diagram to any great degree. It is now apparent that this conclusion requires some

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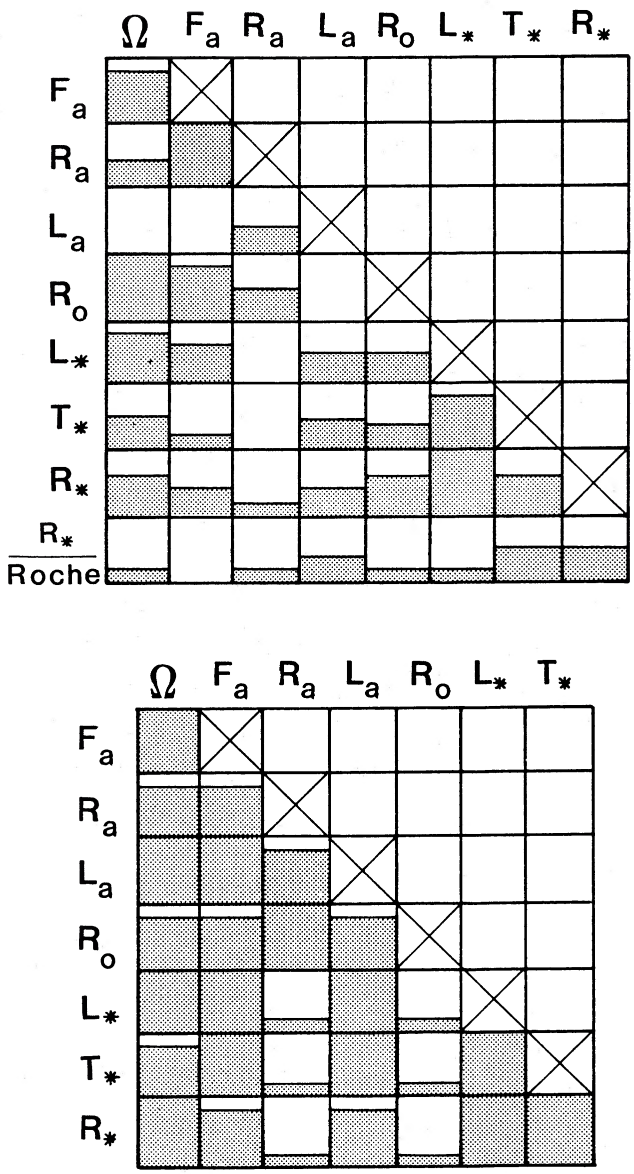

FIG. 3.—A graphical depiction of the level of correlation in evolved synchronized binaries (*top*) and single dwarfs (*bottom*), between various activity diagnostics and some stellar parameters which might have a bearing on stellar activity levels. The squares are filled according to whether the correlation coefficient lies in the first fifth between 0 and 1. (i.e., 0.0–0.2), the second fifth, etc.; completely filled squares indicate a correlation coefficient above 0.8. Note that many things are well correlated in main-sequence stars since they are all rather similar compared with the close binaries which cover a much more disparate group of stars. Note also that tidal coupling in the binaries, expressed as the ratio of stellar to Roche radii, seems to have little to do with the activity levels.

qualification in that it is really only true for the *normalized* activity diagnostic. Not nearly as strong a case can be made for either surface flux or luminosity of activity, especially in main-sequence stars in which these are nearly equivalent. Typically, all luminosity classes were lumped together in earlier papers; in that instance the case is stronger for a general lack of correlation between stellar activity and stellar parameters, but its meaning is less clear.

Since it is also clear that the normalized flux diagnostic, *R*, shows the poorest correlations of the three activity diagnostics in the binaries; I conclude that *this parameter should be dropped as a diagnostic of stellar activity*. Its original motivations were (1) it is observationally easier to determine than the others (not requiring knowledge of the stellar distance or radius) and (2) it was touted as a measure of the efficiency with which the basic energy supply (bolometric luminosity) was converted to nonradiative heating (stellar activity). There is no reason, however, that this efficiency should be similar for two stars with the same bolometric luminosity since there are a great many steps between the production of energy at the core and the appearance of activity on the surface. To choose the most obvious example, if the activity is mediated through production of magnetic fields in a dynamo whose efficiency in turn depends on the stellar rotation, the bolometric luminosity will not be connected with the changes in this production as the star varies its rotation. A number of other factors unrelated to bolometric luminosity (concentration of fields, rate of emergence, proximity of opposite polarities, closing or opening of coronal loops, etc.) may also play a large role in determining the actual activity observed. I suggest that normalization by bolometric luminosity may simply introduce spurious scatter into an activity diagnostic.

Another obvious point is that the tidal coupling parameter shows almost no correlation with any activity diagnostic in the binaries, allowing for the simplified way of calculating it. Since binary activity levels parallel appropriately chosen single stars (§ IV), it would be quite surprising if the tidal coupling had turned out to be important. The conclusion is that the level of activity on the binaries is determined by substantially the same physical mechanisms as on single stars; and while binaries exhibit increased activity levels, these are not related directly to the tidal coupling parameter suggested by Young and Koniges (1977). Of course, such coupling is indirectly important since it provides the spinup of what would otherwise typically be slowly rotating subgiants.

Finally, it is clear that *for the binaries the total luminosity* in activity diagnostics is not correlated with any of the presumed relevant parameters, while surface flux is. This point is discussed in more detail in the next section, but it forms part of the basis for one of the main conclusions of this work—that the surface flux of activity diagnostics is the most meaningful measure of activity.

IV. ACTIVITY AND THE ROSSBY NUMBER

We expect on theoretical grounds that the properties of the convection zone of a star should play a significant role in the production of stellar activity. This should arise both from the necessity of convection to drive a conventional magnetic dynamo and from the need for convective motions as a source of the waves whose dissipation provides the nonradiative heating. The attempts to at least crudely include the convective properties of a star in the analysis of stellar activity has focused on the dimensionless Rossby number: the ratio of rotation period to convective overturn time. This is crudely related to dynamo activity levels according to Durney and Latour (1978). A pioneering paper by Mangeney and Praderie (1984) made the controversial claim that X-ray production from O-M stars was simply related to an effective Rossby number. While there are alternative explanations for X-rays from OB stars, Noyes *et al.* (1984) considered solar-like activity and showed that the Rossby number reduced the scatter compared to using the simple rotation period in correlations with R_{HK}. Basri (1985)

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points out, however, that no advantage is gained in comparison to correlating F_{HK} with the simple rotation period.

With a sample including more evolved objects, the simple relations between luminosity, radius, rotation, and convective properties found on the main sequence break down. The Rossby number should provide better order out of such a sample than rotation period if it contains more of the essential physics. The full sample of stars in this paper provides the first step toward such a test, although there is the added complication that the evolved stars here are in synchronized binary systems. I defer discussion of whether that is important until after the results are presented.

The first issue to settle is again which activity diagnostic to use. I have argued above that R_a is a poor choice, which leaves L_a or F_a. There has been an ongoing discussion (see also Paper I) as to which of these is more fundamental. The argument for the total luminosity is that this is a measure of the total amount of nonradiative energy production on a star, which is *presumed* to be a good measure of the total level of magnetic-field production. Among the problems with this view are (1) we don't know whether it matters how a given amount of total magnetic flux emerging at a stellar surface is organized; (2) whether individual flux tubes would look very different on a giant than a dwarf and how this would affect the emission line fluxes; and (3) the level of dynamo production for a given rotation and convection velocity might also depend on the stellar size; for example, it probably matters whether the dynamo production is distributed throughout the convection zone or concentrated at its lower boundary.

The argument for the surface flux is that for a uniform distribution of activity this would tell us what the average local activity level is, and the effects of stellar radius have been divided out. Among the problems with this are that (1) we know the activity isn't distributed uniformly, so that surface flux is really closer to a measure of activity filling factor than a measure of local properties and (2) if we *presume* that isolated flux tubes look fairly similar from star to star then it is the total rather than local activity which contains the interesting results. It is clear that this debate is based on presumptions which must be clearly demonstrated to be true before it can be resolved. One approach is to get a clue in which direction to go by examining the observations to see whether one or the other of these parameters does the best job of unifying the most diverse results on stellar activity levels.

A controversy has occurred over the interpretation of the result that while RS CVn stars exhibit a nice relationship between rotation and R_x (Walter and Bowyer 1981), they do not show such a relation between L_x and rotation (Pallavicini *et al.* 1981). Furthermore, the former relation is linear, while the latter relation is quadratic for the non–RS CVn sample. The complication of the dependence of stellar parameters themselves on rotation in the RS CVn sample was pointed out by Rengarajan and Verma (1983). In Paper I we disentangled these issues and showed that if the discussion is confined to the above relations it is indeed confusing, but consideration of surface fluxes and, more importantly, other activity diagnostics allows a coherent interpretation to emerge. The recent analysis of this problem by Majer *et al.* (1986) suffers from the same lack of this broader view, allowing them once again to imply that activity in these stars does not depend on rotation. *This is only true for total coronal luminosities.* It should be clear from Paper I and the analysis below that not only does activity (in general) for these stars depend on rotation, but this dependence is the same as for active main-sequence dwarfs. I show below that if one judges the efficacy of a relation between rotation and activity by the lowest scatter and its ability to include the most diverse sample of stars, then it is the surface flux which is the superior measure of activity.

One of the goals of this paper is to examine whether the Rossby number is a significantly better (by the criterion above) measure of "rotation" than the rotation period itself. In order to do this one would like a reliable means of computing the Rossby number. Since convection in stars is not understood much beyond the obviously oversimplified mixing length formulation, a determination of Rossby number will be rather uncertain. This problem is exacerbated off the main sequence. Gilliland (1985) has made an internally consistent set of determinations on and off the main sequence. Cameron-Collier (1985) finds that the peak in Rossby number should occur at the base of the giant branch; a significantly cooler temperature than actually given by Gilliland. Put another way, the effective temperature scale in Gilliland's work does not correspond to the empirical temperature-luminosity relation. Until this is properly corrected, I have adjusted his τ_c–T_{eff} distribution in a somewhat *ad hoc* fashion to reflect a cooler peak (with the expectation that proper new computations will not look very different).[1] The original and adjusted values of the convective overturn time are shown in Figure 4 both on and off the main sequence. The periods used in this analysis are all observational and so are relatively firm. It is better to use the rotation period (if available) than $v \sin i$ to avoid the irrelevant uncertainty in inclinations.

First consider the relation between total luminosity and rotation. I confine the discussion to Mg II (chromospheric) and C II (transition region) since results for the other diagnostics available to *IUE* yield essentially the same information. It is interesting that use of the Rossby number does little to eliminate the fundamental differences between the evolved and main-sequence stars in this measure of activity. As seen in Figure 5, the main-sequence stars show a relatively good relation between L_a and R_0, while the evolved stars show little relation between these parameters. Furthermore, the main-sequence binaries in this sample appear to lie along an extension of the single dwarf relation. Advocates of L_a as the fundamental activity measure see this as a reason to exclude the RS CVn stars from a rotation-activity analysis, but the picture is very different if one considers F_a instead. One can argue which of these two is really the more meaningful according to some preconceptions, but the data clearly show that surface flux is better at unifying stellar activity on and off the main sequence. It is unsurprising that they both work on the main sequence.

These results are interesting in the context of understanding the production levels of stellar activity. The implication is that as one adds area to the stellar surface, one increases the total nonradiative energy production from the star. An evolved star with the same Rossby number as a main-sequence star but several times the radius tends to have a higher total luminosity in activity diagnostics, although there is not a tight relation and the distinction blurs as one looks at the most active dwarfs. One possible explanation is that the Rossby number is

[1] This explains part of the difference between this work and a preliminary version of this analysis (Basri 1985). That work also contained an unfortunate error between the main-sequence and post–main-sequence values which exaggerated differences between them.

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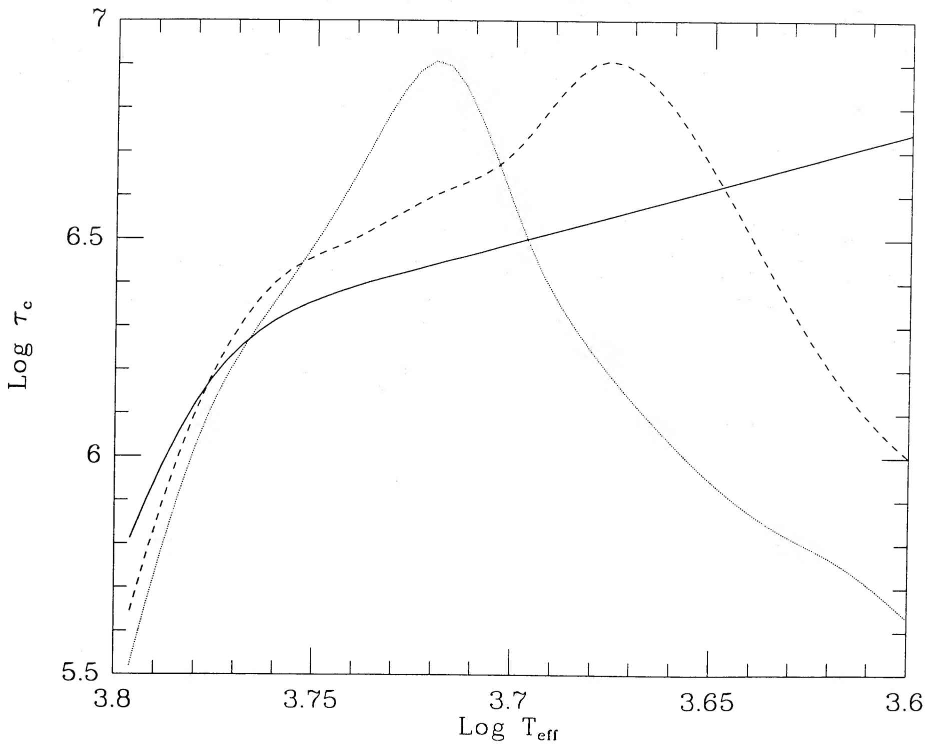

FIG. 4.—The convective overturn times adopted from Gilliland (1985). *Solid line:* main-sequence stars. *Dotted line:* his relation for post–main-sequence stars. *Dashed line:* actual relation used for these stars after correction of the effective temperature scale.

not the appropriate means of characterizing the independent parameter. Another is that since the evolved stars here are in synchronized systems, their luminosity is further enhanced somehow by this effect (for example, by an increase in the radial differential velocity gradient). This may indeed be a factor, as discussed below.

The relations between surface flux and period are shown in the top panels of Figure 6. There is a vertical scatter in these of about half an order of magnitude; this is the intrinsic level of scatter expected based on the known variability of individual stars (including the Sun) on both short time scales and over stellar activity cycles. It appears that an exponential rather than a power law might be more appropriate for Mg II; similar results are found by Simon and Fekel (1987; hereafter SF). I have not made explicit fits to particular relations here because there is no real theoretical understanding of what form of relation to expect. There is a possibility that the Mg II relation is somewhat contaminated by a component of flux less sensitive to the magnetic field, e.g., acoustic heating. Zwaan (1985) and Schrijver (1985) have shown that subtracting a basal chromospheric level from chromospheric diagnostics improves the correlations.

The main point is that this representation of a "rotation-activity" connection does a good job of unifying a rather diverse sample of stars, suggesting that it may actually be telling us something about what fixes activity levels. The dynamic range in C II is larger than for Mg II, so the relation is clearer there. One might expect additional scatter in surface flux relations compared with total luminosity and especially compared with a luminosity ratio, since both the uncertain stellar distance and radius enter into F, only the distance enters into L, and none of those are involved in R. This makes the fact that relations involving F show the least actual scatter even more compelling. Essentially the same conclusion is reached by Zwaan (1985) on somewhat different grounds. It seems clear that surface fluxes are the most heuristic diagnostic of activity.

What happens if the Rossby number is used as the abscissa instead of simple rotation period? This is shown in the lower panels of Figure 6 and is more clearly studied using C II because of its increased dynamic range. There are three binary systems which appear unusually inactive for their Rossby number; SF argue that 33 Psc and o Dra may not have the rotation period previously ascribed to them. Otherwise, all the stars, both on and off the main sequence, lie along fairly well-defined lines in the log-log plane. The main effect of using P instead of R_0 appears to be that the binary subgiants are fairly well mixed with the single dwarfs when using R_0, while they lie on a parallel line about half an order of magnitude above the dwarfs (at a given period) using P. The subgiants are larger, cooler stars for which the convective overturn times are longer. This keeps their Rossby numbers closer to the smaller stars at a given period which have similar activity levels. Keeping in mind the uncertainties in both stellar mass and Rossby number, this provides tentative evidence that the Rossby number does indeed contain additional information on a physical quantity relevant to the determination of activity levels (namely, the convective overturn time). In any case, Figure 6 provides unambiguous evidence that stellar activity has a clear dependence on stellar rotation over a wide variety of stellar types and systems.

To go further, we must consider the fact that the two stellar samples differ in two independent but conceivably important ways: duplicity and evolutionary status (luminosity class). In the top panels of Figure 6, there is a clear tendency for the binaries to be more active than single stars with the same rotation period. The same effect is very obvious in Figure 7 of

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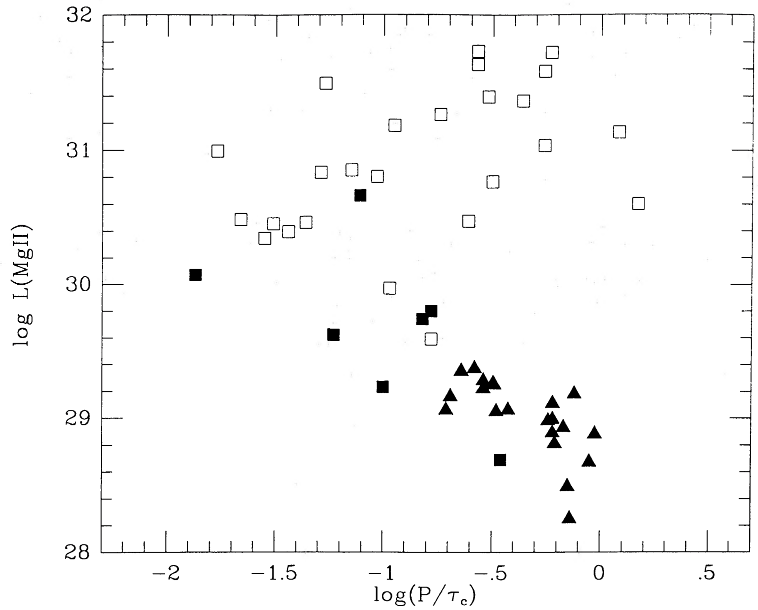

FIG. 5a

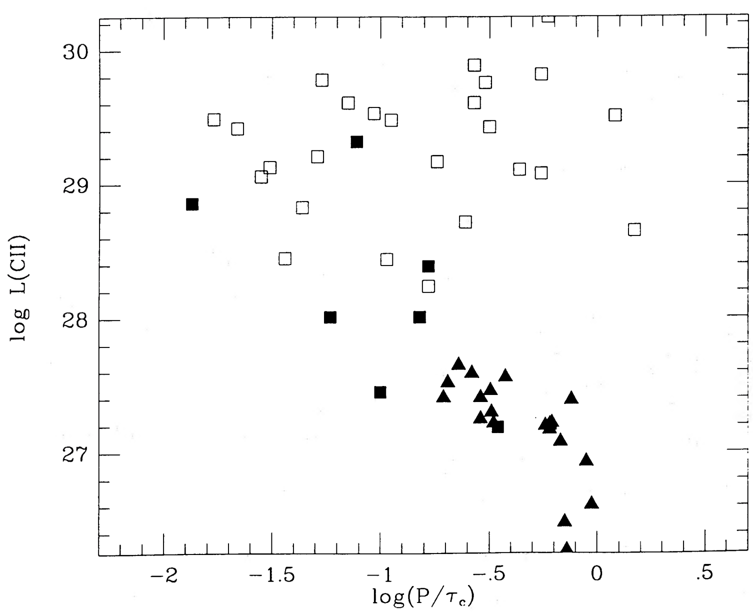

FIG. 5b

FIG. 5.—Relation between total activity luminosity and Rossby number. (*a*) log *L*(Mg II). (*b*) log *L*(C II). The symbols are as in Fig. 1. Note that stars of different luminosity classes are certainly not brought together onto a single relation by use of the Rossby number. This is also true if rotation period is used as the abscissa.

SF. It is also true that most of the binaries here are more evolved than their single counterparts. In order to separate these effects, a larger sample is required which includes single evolved stars and more unevolved stars in close binary systems. The former pose a difficult problem since most single evolved stars tend to be both slow rotators and inactive. The sample of evolved single stars can be increased, although active stars are likely to dominate because they stand out observationally and it is very difficult in general to determine rotation rates for the slow single giants and subgiants.

The sample of unevolved stars in close binary systems is already increased in the recent work of SF. The mix of spectral types is similar for the binaries and the single stars, although the later type binaries are more rapidly rotating than their single counterparts. In the sample here, the unevolved binaries are skewed to earlier spectral types but appear to lie along the same relation as the subgiants. There are too few points, however, and this appearance is driven by three systems around 10 day periods. In the larger sample of SF, the unevolved binaries appear to lie on an extension of the power law for single stars (excluding the very early spectral types) to shorter periods. It would appear that duplicity is a factor in increasing the activity of stars with the same luminosity largely through its effect on rotation. Note that this conclusion applies

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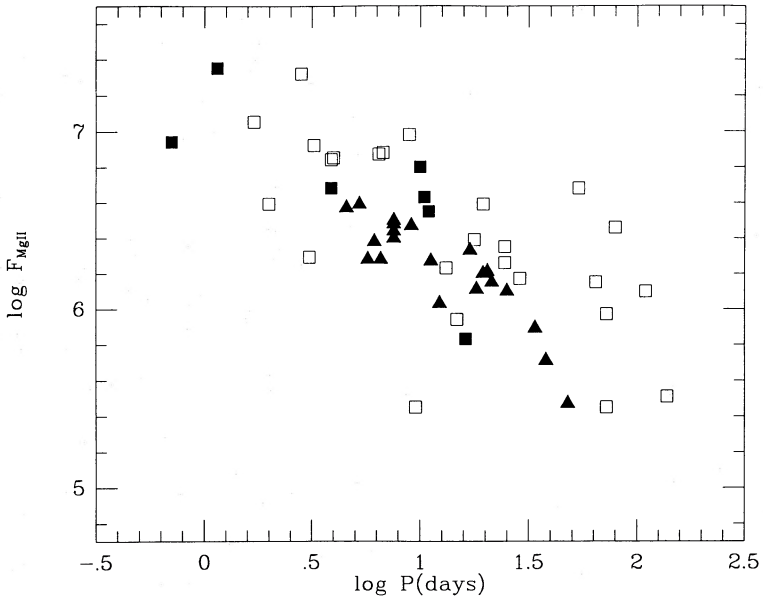

FIG. 6a

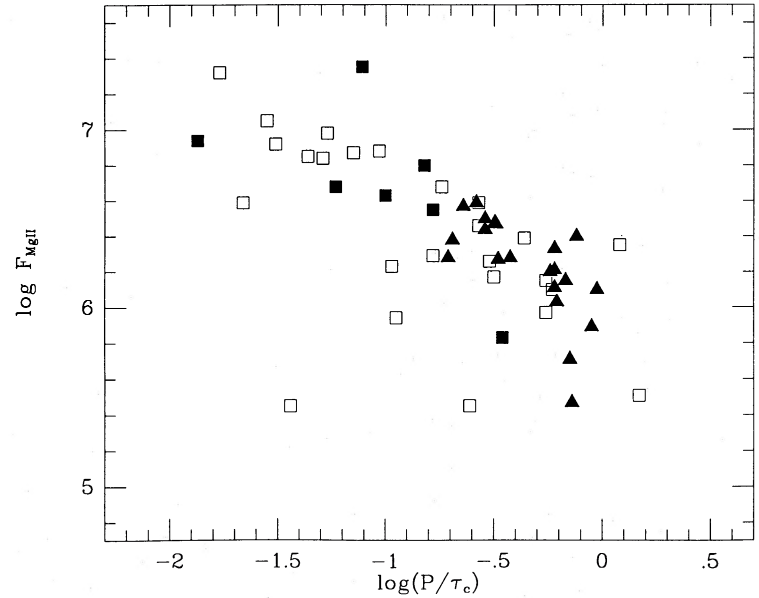

FIG. 6b

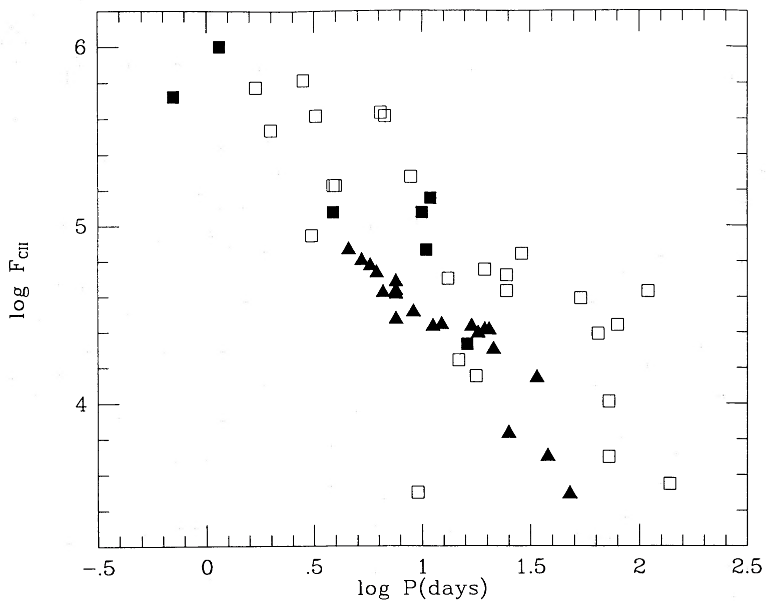

FIG. 6c

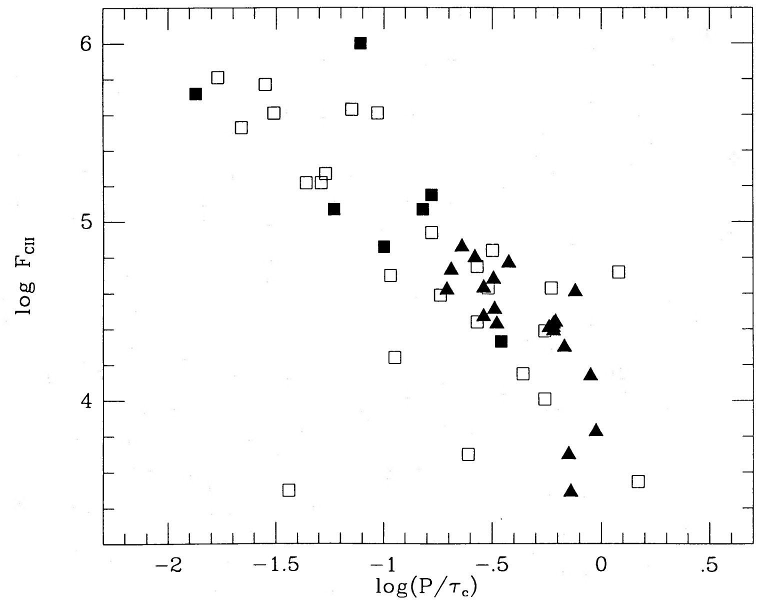

FIG. 6d

FIG. 6.—Rotation-activity relations for the full sample using the surface flux as the appropriate activity measure. (*a*) log $F_{Mg\,II}$. (*b*) log $F_{C\,II}$. (*c*) log $F_{Mg\,II}$. (*d*) log $F_{C\,II}$. Symbols are as in Fig. 1. Both the rotation period (*a*–*b*) and the Rossby number (*c*–*d*) yield good relations. The full sample seems to lie more on a single relation with Rossby number. The period relations are perhaps less scattered within the dwarfs and subgiants separately, and the binary subgiants are on a parallel but more active tract at a given period. There is no clear preference from these data for Rossby number or period as the best "rotation" measure.

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to activity as measured by surface flux and rotation as measured by period. If duplicity itself is not a factor, the exponential laws for different spectral types in SF would be less consistent with the full sample than a single power law through all the main-sequence stars. The very early spectral types fall below this, presumably because their convection zones are very thin and the Rossby number is rapidly decreasing.

The tentative conclusion is that the evolved binaries lie above their main-sequence counterparts due more to their evolutionary status than their duplicity. The Rossby number analysis here suggests that their activity levels are consistent with single stars of similar Rossby number, and that the separation in the $F-P$ plane is due largely to the different convective zone properties. It is clear that more refined calculations of Rossby numbers over a wide range of stellar masses and temperatures are an urgent requirement for further progress. It is also clear that much larger samples of stars with similar stellar parameters need to be analyzed before this conclusion could be considered to be firm. One implication is that single evolved stars should be more active than their main-sequence counterparts with the same rotation period.

V. SUMMARY OF CONCLUSIONS

The main thrust of this paper is that a unification of the many observations and types of analysis in the study of stellar activity is emerging. Stellar activity exhibits some fundamental similarities across a very wide range of activity levels and types of stars. Perhaps the most solid of these similarities is the relation that different activity diagnostics bear toward each other. Not a new result, the fact that stellar activity can be characterized by one or two parameters (either the flux in a particular well-chosen diagnostic or an appropriate combination of several fluxes) is reinforced by this work. This means that activity structures are apparently similar in a wide variety of circumstances and constitutes indirect evidence that most of the range in activity levels observed is due to different covering factors of activity rather than drastic changes in the structure of individual flux tubes. It also means that one does not learn something fundamentally different about the basic level of activity by studying several different diagnostics. Thus the decay of "activity" with age, for example, or the dependence of "activity" on rotation can really be expressed as single relations and reasonably studied with one or two of the best diagnostics.

Another unification suggested is that the appropriate measure of "activity" is the surface flux in a given emission line or bandpass. The efficacy of the several other possible choices for expressing observational data are examined and surface flux is shown to yield the clearest results when stars of very disparate spectral types, luminosities, and duplicity are studied together. I suggest that the use of normalized rather than surface fluxes merely introduces a spurious dependence on $T_{\rm eff}$ which obscures rather than clarifies studies of stellar activity. The use of total luminosity is shown to be empirically inappropriate for stars of very different luminosity types; theoretical arguments to the contrary notwithstanding.

This is the first quantitative attempt to discover whether the Rossby number unifies stars both on and off the main sequence in a single rotation-activity relation. Although there are still disturbing uncertainties in calculating Rossby numbers, the results here are promising. Specifically, use of the Rossby number seems to mix binary subgiants and single dwarfs together along a single rotation-activity relation. This is aesthetically pleasing, although it is not known *a priori* that they actually belong together. Use of period instead of Rossby number also yields a clean result, but the (evolved) binaries are offset to higher activity at a given period. Combining my results with a recent study by SF leads to the conclusion that when the confusion between luminosity class and duplicity is reduced by considering only unevolved close binaries, the Rossby number can explain most of the features in the data. It is still not possible, however, to rule out an independent role for duplicity itself, so it is premature to prefer period or Rossby number on an observational basis. Studies of the dependence of activity on both should be pursued with more complete samples of stars until a clear preference can be demonstrated. Such studies should uniformly employ surface flux as the measure of activity.

It is clear, however, that there is a fundamental connection between some measure of stellar rotation (perhaps modified by information on convection) and the level of stellar activity. This relation holds for very different types of stars and over a wide range of stellar ages. It holds in the RS CVn systems, in other close binaries, and in convective single stars of many different ages, luminosities, and effective temperatures. This is clearly a fruitful area for further investigation.

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