Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 15 November 1998 (MN LaTeX style file v1.4)

On the rotation-activity correlation for active binary stars

A. G. Gunn[1,2]⋆, C. K. Mitrou[2,3] and J. G. Doyle[2]
[1] *University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire, SK11 9DG, UK*
[2] *Armagh Observatory, College Hill, Armagh, BT61 9DG, N. Ireland*
[3] *Section of Astrophysics, Astronomy and Mechanics, Dept. of Physics, University of Athens, Athens 15783, Greece*

Accepted 1997 Received 1997 in original form June 1997

ABSTRACT

We present an investigation of rotation-activity correlations using *International Ultraviolet Explorer (IUE)* SWP measurements of the CIV emission line at 1550Åfor 72 active binary systems. We use a standard stellar evolution code to derive non-empirical Rossby numbers, R_o, for each star in our sample and compare the resulting CIV rotation-activity correlation to that found for empirically derived values of Rossby number and that based on rotation alone. For dwarf stars our values of R_o do not differ greatly from empirical ones and we find a corresponding lack of improvement in correlation. Only a marginal improvement in correlation is found for evolved components in our sample. We discuss possible additional factors, other than rotation or convection, that may influence the activity levels in active binaries. Our observational data implies, in contrast to the theoretical predictions of convective motions, that activity is only weakly related to mass in evolved stars. We conclude that current dynamo theory is limited in its application to the study of active stars because of the uncertainty in the angular velocity-depth profile in stellar interiors and the unknown effects of binarity and surface gravity.

Key words: stars: activity - stars: late type - stars: binaries: close - stars: flare - stars: variables

1 INTRODUCTION

The work of Wilson (1963), Kraft (1967) and Skumanich (1972) led to the hypothesis that rotation plays a crucial role in the generation of stellar magnetic activity. This is evident in strong correlations of magnetic activity indicators with rotational velocities, rotational periods, or, in the case of synchronously rotating members of close binary systems, orbital periods. For single stars relations have been reported between rotation and coronal emission (Pallavicini et al. 1981; Walter 1981; Schrijver, Mewe & Walter 1984; Jordan & Montesinos 1991; Montesinos & Jordan 1993; Hempelmann et al. 1995), chromospheric emission (Middelkoop 1981; Hartmann et al. 1984) and transition region line fluxes (Vilhu 1984). For RS CVn systems, generally containing at least one evolved component, similar rotation-activity correlations have been found in UV line fluxes (Oranje, Zwaan & Middelkoop 1982; Vilhu & Rucinski 1983; Basri, Laurent & Walter 1985), Hα and CaII emissions (Strassmeier et al. 1989), X-rays (Walter & Bowyer 1981) and in the radio region (Drake, Simon & Linsky 1989; Gunn 1996).

The observance of chromospheric activity in main-sequence stars with (B–V) $\geq$ 0.4 suggests that it coincides with the onset of a convective envelope and is therefore a result of a dynamo mechanism (Parker 1970, 1977). Using this assumption Durney & Latour (1978) showed that the level of activity should be a function of rotational period, P_{rot}, divided by an appropriate convective turnover time-scale, τ_c, in the outer convection zone. This dependence on Rossby number (R_o=P_{rot}/τ_c) was confirmed by Noyes (1983) who found that CaII emission levels could be approximated by the product of angular rotation rate and a function of spectral type similar to τ_c for main-sequence stars. R_o is an important indicator in hydro-magnetic dynamo theory and measures the extent to which rotation can induce both helicity and differential rotation required for dynamo activity.

The variation of τ_c along the lower main-sequence has been studied using stellar evolution and structure codes (Gilman 1980; Gilliland 1985; Kim & Demarque 1996). Although there are inherent differences in the formulation of the mixing length theory used to describe convective motion these studies all generally agree on the form of the (B–V)-τ_c relationship for main-sequence stars. For (B–V) $\geq$ 0.8 the variation of τ_c is small so magnetic activity is more heavily dependent on rotation. The overall chromospheric activity is found to be well parametrised by an *empirical* Rossby number (Noyes et al. 1984; Stępień 1994) whose functional

⋆ email: agg@jb.man.ac.uk (AGG), kam@rigel.da.uoa.gr (CKM), jgd@star.arm.ac.uk (JGD)

dependence on (B–V) is obtained from the observational data themselves. For example, Noyes et al. (1984) derived a (B–V)-τ_c dependence by minimising the scatter for an empirical fit to the models of Gilman (1980). This semi-empirical relationship is therefore inappropriate for a study of rotation-activity correlations in anything other than the original sample of main-sequence stars.

The main drawback of the Noyes et al. (1984) relationship is that it does not apply to the evolved components of active binaries. The evolved state of these stars (see Barrado et al. 1994) places them in a region of the HR diagram where the internal structure is significantly altered from main-sequence stars. Consequently activity levels may undergo quite rapid variations over a narrow range of temperature. However, studies to date consistently indicate the dynamo generation of activity from the lower chromosphere through the corona, although the dependence on luminosity class, spectral type and binarity is far from clear. Given the ad hoc nature of *empirical* (B–V)-τ_c relationships and the complexity of convection zone dynamical evolution the only method of studying the dependence of activity on Rossby number is to use theoretical (non-empirical) values. Although the variability of convective parameters during post-main-sequence evolution is found to be quite complex (Gilliland 1985) models are sufficiently refined to be of use.

This paper reports our attempts to study the rotation-activity correlation for a sample of 72 active binaries using the C IV emission line detected by the IUE (International Ultraviolet Explorer) and non-empirical values of Rossby number. This is a viable test of the applicability of current dynamo theory to stellar activity, since, for evolved stars, with the large departure of τ_c from the values corresponding to main-sequence stars of the same (B–V), a significant increase in correlation should be found using non-empirical R_o as opposed to empirical R_o or P_{rot}. In Section 2 we describe the observations of our sample, in Section 3 we introduce our assumptions and describe the sample, in Section 4 we discuss the stellar evolution code used to model the stellar interiors and in Section 5 we discuss the results of our analysis.

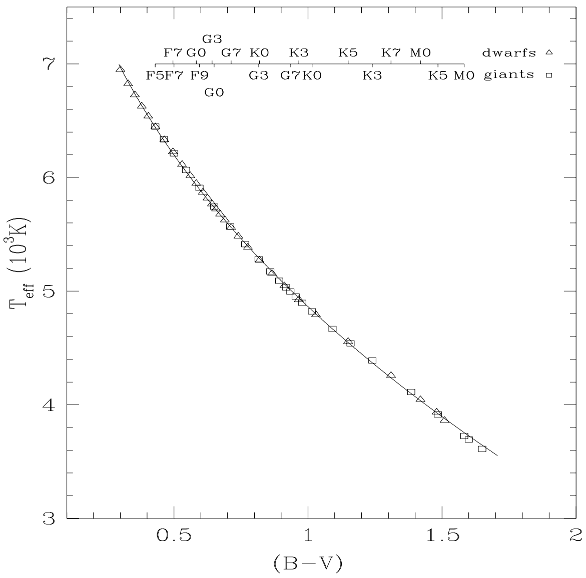

Figure 1. Relationship between (B–V) colour index and effective temperature for dwarf stars (triangles) and giant stars (squares) taken from Gray (1992). A single polynomial fit (solid line) is sufficient for both dwarfs and giants between spectral types F0 and M2 but with a shift in spectral type-temperature correspondence (shown on diagram).

2 OBSERVATIONS

As activity indicator in this rotation-activity study we used the flux radiated in the C IV emission lines at 1548Å and 1551Å. This doublet originates in the transition region and features as the strongest line (showing as a single line at ∼ 1550Å) in the low-resolution SWP IUE spectra. The line flux is representative of the total radiative losses due to mechanical heating. This conclusion is based on work by Doyle (1996a) who showed that a relationship (originally derived from solar data by Bruner & McWhirter 1988) exists between the C IV 1550Å line flux and the total radiative losses as derived by an emission measure technique for active dwarfs and sub-giants. There is however some evidence that this may under-estimate the radiative losses for the faster rotators (Houdebine et al. 1996; Doyle 1996b) although this is still questionable. We note that C IV λ1550 measurements have previously been used in rotation-activity correlation studies for single and binary stars by Vilhu & Rucinski (1983), Basri, Laurent & Walter (1985), Basri (1987), Rutten & Schrijver (1987) and Simon & Fekel (1987). Basri, Laurent & Walter (1985) rejected the use of luminosities in their study of F to K dwarfs whilst Rutten & Schrijver (1987) found empirically that the flux density F, not luminosity L, was the appropriate unit for studies of magnetically controlled radiative emission. Some authors have chosen to adopt a normalised flux $R = F/\sigma T^4_{eff}$ which may or may not improve correlations. In our study we have adopted the standard practice of analysing correlations with surface flux F_{CIV} which necessarily draws errors in radii and distances into the results.

Our sample of stars consists of 72 active binary systems listed by Strassmeier et al. (1993) that have been observed with the SWP camera on the IUE. We excluded any systems with unknown distances and/or radii, those which contain white dwarf components and stars with masses 0.4M$_\odot$ > M > 2.2M$_\odot$ since our convective models are unreliable for masses outside this range (see Section 4). We conducted a full search of the IUE archives and collected for each system those data that were available by June 1996. To analyse the IUE images we used the STARLINK packages IUEDR (Giddings et al. 1996) and DIPSO (Howarth, Murray & Berry 1996). For the determination of the C IV flux, we used the average of several (quiescent) spectra whenever possible. The emission line fluxes in Table 2 were derived by averaging the value from a least squares gaussian fit to the line and the value of a trapezoidal integration. The two averaged values usually differed by less than 10%. We attributed the total of the observed flux to the active component (as defined in Strassmeier et al. 1993), unless both components were characterised as Ca II emitters, in which case we divided the observed flux equally between them. A zero value in the last column of Table 2 indicates that the flux originates from the

Table 1. The individual parameters for the stars in the sample (see text for description). Notes: (1) inferred from (B–V) or from the spectral type using the results of Gray (1992), (2) Basri, Laurent & Walter (1985), (3) Simon & Fekel (1987), (4) Dempsey et al. (1993), (5) Cayrel de Strobel et al. (1994), (6) Donati, Henry & Hall (1994), (7) Drake, Simon & Linsky (1989), (8) Slee et al. (1987), (9) Singh, Drake & White (1996), (10) mass estimated from the star's position in our HR diagram. The luminosity class of the secondary component of AR Psc is taken from Fekel, Mofett & Henry (1986).

		Hot Component						Cool Component						
Index	Name	Class	$R_\star$ ($R_\odot$)	Note	$M_\star$ ($M_\star$)	Note	T_{eff} (K)	Class	$R_\star$ ($R_\odot$)	Note	$M_\star$ ($M_\star$)	Note	T_{eff} (K)	Temperature Code
1	AP Psc							III	41.0		1.90	10	4106	b
2	13 Cet	V	1.25	1	1.26	1	6214	V	1.3	4	1.00	1	5708	c
3	CF Tuc	IV	1.67		1.06		5948	IV	3.32		1.21		4452	c
4	BI Cet	V	0.90		0.96	1	5570	V	0.90		0.96	1	5570	a
5	AR Psc	V						IV	1.52	9	1.18		5162	a
6	UX For	V	1.00	1	0.94	1	5516	V	1.00	1	0.94	1	5516	c
7	LX Per	IV	1.64		1.24		6004	IV	3.05		1.32		4998	a
8	UX Ari	V	0.83		0.93		5678	IV	5.43		1.09		5048	c
9	V711 Tau	IV	1.30		1.10		5385	IV	3.90		1.40		4912	c
10	V837 Tau	V	1.05		1.00		5819	V	0.74		0.67		4557	c
11	AG Dor	V	0.85	1	0.79	1	4976							b
12	V818 Tau	V	0.93	1	0.95	1	5626	V	0.67	1	0.64	1	4408	c
13	27691	V	1.14	1	1.12	1	6004							b
14	V833 Tau	V	0.68	1	0.70	1	4680							b
15	3 Cam	III	12.00	7	1.90	10	4712							b
16	12 Cam	III	16.00	2	2.00	10	4608							b
17	TW Lep	IV						III	10.5	4	1.20	10	4540	b
18	V1149 Ori	III	15.0	3	1.80	10	4568							b
19	SZ Pic	V	0.92	1	0.85	1	5310							b
20	TY Pic	V						III	7.00	8	1.50	10	4820	c
21	OU Gem	V	0.75	1	0.74	1	4925	V	0.63	1	0.68	1	4557	c
22	TZ Pic	III	12.0	7	1.40	10	4546							c
23	SV Cam	V	1.11		0.93		5793	V	0.74		0.67		4791	c
24	σ Gem	III	14.00	4	1.80	10	4608							b
25	54 Cam	IV	3.14		1.64		5964	IV	2.64		1.61		5385	c
26	VX Pyx	III	10.0	8	1.20	10	4976							b
27	TY Pyx	IV	1.59		1.22		5546	IV	1.68		1.20		5436	a
28	IL Hya	III	12.00		2.20	10	4820							b
29	IN Vel	III	20.0	8	2.10	10	4506							b
30	DH Leo	V	0.97		0.83		5273	V	0.67		0.58		4258	c
31	DM UMa	III	5.90		1.10	10	4722							b
32	ξ UMa(B)	V	0.86	5	0.85	5	5912							a
33	EE UMa	III	16.0	7	1.00		4312							b
34	HU Vir	IV	6.30		1.40	10	4820							b
35	DK Dra	III	14.30		1.92		4611	III	14.30		1.92		4611	a
36	AS Dra	V	0.97	1	1.00	1	5723	V	0.84	1	0.85	1	5386	c
37	IL Com	V	1.10		0.85		6138	V	1.10		0.82		6138	a
38	RS CVn	IV	1.99		1.44		6478	IV	4.00		1.44		5068	a
39	114630	V	1.05	1	1.11	1	5880	V	1.05	1	1.11	1	5880	a
40	BL CVn	IV						III	14.80		1.33		4568	b
41	BM CVn	III	16.00	3	1.70	10	4526							b
42	BH CVn	IV	3.10		1.50		6727	IV	2.85		0.80		4794	c
43	V851 Cen	IV	3.50		0.80	10	4718							b
44	UV CrB	III	16.1	4	1.06		4368							b
45	GX Lib	V						III	8.25		1.70	10	4820	b
46	LS TrA	IV	2.83	8	0.80	10	4778	IV	2.83	8	0.90	10	4778	a
47	TZ CrB	V	1.22		1.12		6332	V	1.21		1.14		5948	c
48	WW Dra	IV	2.12		1.36		5880	IV	3.90		1.34		4650	a
49	V792 Her	IV	2.58		1.41		6370	III	12.3		1.47		4714	a

Table 1. continued.

		Hot Component						Cool Component						
Index	Name	Class	$R_\star$ ($R_\odot$)	Note	$M_\star$ ($M_\star$)	Note	T_{eff} (K)	Class	$R_\star$ ($R_\odot$)	Note	$M_\star$ ($M_\star$)	Note	T_{eff} (K)	Temperature Code
50	V824 Ara	IV	1.61		1.11		5385	IV	1.25		1.03		5048	c
51	Z Her	IV	1.85		1.61		6540	IV	2.73		1.31		5048	c
52	V772 Her	V	1.00		1.04		5914							b
53	V815 Her	V	0.97		0.99		5542							b
54	o Dra	III	14.30		1.40	10	4466							b
55	V775 Her	V	0.85		0.82	1	5273							c
56	V478 Lyr	V	0.94		0.89	1	5490							b
57	V1762 Cyg	III	9.20		1.40	10	4670							b
58	V4139 Sgr	III	20.0	8	1.70	10	4406							b
59	V1764 Cyg							III	24.9		1.50		4350	b
60	ER Vul	V	1.07		1.10		5948	V	1.07		1.10		5678	c
61	AS Cap	III	14.0	7	2.00	10	4668							b
62	42 Cap	IV	3.00	2	1.50	10	5738							b
63	RT Lac	IV	3.40		1.66		5140	IV	4.20		0.78		4886	c
64	HK Lac	V						III	15.00	2	2.20	10	4692	b
65	AR Lac	IV	1.52		1.23		5616	IV	2.72		1.27		5048	c
66	V350 Lac	III	12.70		1.10		4506				0.90			b
67	IM Peg	III	7.00		1.00	10	4608							b
68	TZ PsA	V	0.95	1	0.90	1	5570							b
69	RT And	V	1.17		1.50		6115	V	0.84		0.99		5273	c
70	SZ Psc	IV	1.50		1.28		6406	IV	5.10		1.62		4864	a
71	λ And	III	7.00	6	1.30	10	4842							b
72	II Peg	IV	2.20		0.90	10	4842							b

hot component, a 1 that the cool component is the active one and 0.5 that both stars contribute equally. Some of the systems have not been extensively observed by the IUE so that fluxes are sometimes based on a single measurement. Such values may well be susceptible to general variability, flare activity or orbital phase dependence. We have followed the usual practice of arbitrarily ascribing half of the emission to each component, for systems where both stars are known to be active, this, in addition to the empirical flux uncertainty, places some question on the accuracy of the fluxes. A flux error estimate is also difficult to provide since it depends on the S/N of individual spectra and the subjective position of the continuum. Based on a comparison of our two methods of deriving f we estimate that the errors are $\sim$10% (comparable to those given by Simon & Fekel 1987) but may be much higher for systems with two active components. We emphasise, however, that this sample is the most accurate and up-to-date compilation of C IV λ1550 fluxes for active binary stars. For several stars in our list C IV fluxes are given for the first time.

3 STELLAR PARAMETERS

The parameters of the sample stars are shown in Table 1 where we list an arbitrary index number in increasing RA, the stars' more usual name or HD number, luminosity classes, radii, masses, and effective temperatures for hot and cool components and a code for our temperature assignment (see below). In Table 2 we list for each star the distance in parsecs, the rotation period P_{rot}, the C IV λ1550 emission line flux observed at Earth, f_{CIV}, in units of 10^{-13} erg cm^{-2} s^{-1}, the convective turnover time-scales (in days) resulting from our modelling (see Section 4) and those derived using the semi-empirical (B–V)-log τ_c relationship of Noyes et al. (1984), and a code indicating to which star the flux is attributed (see Section 2). Unless explicitly stated otherwise we used values for periods, distances, spectral types, luminosity classes, colours, radii and masses given by Strassmeier et al. (1993). In this study we assume all stars in our sample display orbital-rotational synchronicity. Classically the period limit for synchronicity is $\sim$ 20 days (Linsky 1983) for dwarfs and subgiants but is possibly much higher for giants. In our sample 27% of stars have $P_{orb} \geq 20$ days but only 17% are listed as showing evidence of asynchronism in the study by Tan, Wang & Pan (1991).

Gray (1992) lists (separately for dwarfs and giants) the correspondence between (B–V) colour and temperature for a wide range of spectral types. Fitting these data with a third order polynomial, we derived the relation between (B–V) and log T_{eff} which is shown in Figure 1. Note that a single polynomial suffices to fit the data for both dwarfs and giants of spectral types between F0 and M2. We therefore derived temperatures for each component using the above (B–V))-

Table 2. Additional parameters and results for the sample (see text for details). Notes: (1) Drake, Simon & Linsky (1989), (2) Slee et al. (1987).

		System Parameters				Hot Component		Cool Component		
Index	Name	Distance (pc)	Note	$\log P_{rot}$ (days)	f_{CIV} (10^{-13} erg cm^{-2} s^{-1})	$\log \tau_c(E)$ (days)	$\log \tau_c(NE)$ (days)	$\log \tau_c(E)$ (days)	$\log \tau_c(NE)$ (days)	Activity
1	AP Psc	140		1.984	4.1			1.415	1.076	1
2	13 Cet	21		0.318	2.8			1.099	1.182	1
3	CF Tuc	54		0.447	4.2			1.390	1.481	1
4	BI Cet	60		-0.288	1.4	1.186	1.237	1.186	1.237	0.5
5	AR Psc	17		1.155	6.4			1.329	1.743	1
6	UX For	35		-0.020	3.2	1.214	1.256	1.214	1.256	0.5
7	LX Per	130		0.905	1.0			1.351	1.940	1
8	UX Ari	71		0.809	15.5			1.346	1.750	1
9	V711 Tau	36		0.453	38.1			1.359	1.967	1
10	V837 Tau	55		0.286	6.5	1.034	1.123			0
11	AG Dor	32		0.409	3.7	1.353	1.390			0
12	V818 Tau	45		0.750	0.2			1.394	1.510	1
13	27691	45		0.602	0.4	0.840	0.977			0
14	V833 Tau	17		0.252	3.4	1.375	1.452			0
15	3 Cam	85		2.083	2.0	1.372	1.913			0
16	12 Cam	134		1.908	2.9	1.379	1.845			0
17	TW Lep	220		1.452	1.6			1.384	1.587	1
18	V1149 Ori	164		1.729	2.4	1.382	1.751			0
19	SZ Pic	30		0.695	1.5	1.295	1.312			0
20	TY Pic	110		2.028	1.1			1.365	1.898	1
21	OU Gem	12		0.845	1.8	1.357	1.403	1.383	1.477	0.5
22	TZ Pic	160	1	1.135	1.1	1.383	1.642			0
23	SV Cam	74		-0.227	0.7			1.366	1.432	1
24	σ Gem	59		1.292	35.2	1.379	1.800			0
25	54 Cam	38		1.044	2.6	0.872	0.660	1.270	1.642	0.5
26	VX Pyx	135		1.654	1.6	1.353	1.918			0
27	TY Pyx	55		0.505	4.5	1.201	1.448	1.250	1.540	0.5
28	IL Hya	138		1.111	4.0	1.365	2.033			0
29	IN Vel	590	2	1.718	0.3	1.386	1.733			0
30	DH Leo	32		0.030	2.8			1.405	1.544	1
31	DM UMa	130		0.875	1.0	1.372	1.776			0
32	ξ UMa(B)	7.9		0.600	8.3	0.931	1.062			0
33	EE UMa	195	1	1.874	0.3	1.400	1.317			0
34	HU Vir	220		1.017	5.0	1.365	1.900			0
35	DK Dra	130		1.809	4.6	1.379	1.825	1.379	1.825	0.5
36	AS Dra	29		0.733	1.5	1.099	1.176	1.270	1.294	0.5
37	IL Com	86		-0.017	2.1	0.699	0.822	0.699	0.822	0.5
38	RS CVn	180		0.681	5.0			1.343	1.911	1
39	114630	25		0.627	2.2	0.960	1.084	0.969	1.084	0.5
40	BL CVn	300		1.272	1.9			1.382	1.643	1
41	BM CVn	250		1.314	5.5	1.384	1.680			0
42	BH CVn	53		0.417	17.2			1.368	1.815	1
43	V851 Cen	80		1.079	4.0	1.372	1.795			0
44	UV CrB	230		1.271	2.4	1.396	1.357			0
45	GX Lib	219		1.047	1.7			1.365	1.945	1
46	LS TrA	96	2	1.694	2.9	1.368	1.836	1.368	1.836	0.5
47	TZ CrB	21		0.057	18.1	0.441	0.499	0.902	1.030	0.5
48	WW Dra	180		0.666	0.9			1.376	1.737	1
49	V792 Her	310		1.440	1.0			1.372	1.822	1

Table 2. continued.

		System Parameters				Hot Component		Cool Component		
Index	Name	Distance (pc)	Note	$\log P_{rot}$ (days)	f_{CIV} (10^{-13} erg cm^{-2} s^{-1})	$\log \tau_c(E)$ (days)	$\log \tau_c(NE)$ (days)	$\log \tau_c(E)$ (days)	$\log \tau_c(NE)$ (days)	Activity
50	V824 Ara	39		0.226	7.1	1.270	1.553	1.346	1.750	0.5
51	Z Her	100		0.601	1.8			1.346	1.883	1
52	V772 Her	42		-0.056	3.2	0.931	1.060			0
53	V815 Her	31		0.258	4.5	1.201	1.246			0
54	o Dra	138		2.141	2.9	1.389	1.531			0
55	V775 Her	24		0.459	2.6	1.302	1.323			0
56	V478 Lyr	26		0.328	2.7	1.227	1.265			0
57	V1762 Cyg	90		1.456	6.3	1.375	1.778			0
58	V4139 Sgr	480	2	1.655	0.5	1.393	1.475			0
59	V1764 Cyg	390		1.604	1.0			1.397	1.346	1
60	ER Vul	46		-0.156	4.0	0.902	1.030	1.119	1.197	0.5
61	AS Cap	360	1	1.691	0.9	1.375	1.899			0
62	42 Cap	34		1.120	4.3	1.079	1.210			0
63	RT Lac	205		0.705	1.1	1.333	1.907	1.360	1.742	0.5
64	HK Lac	150		1.388	2.8			1.373	1.957	1
65	AR Lac	47		0.297	13.9	1.154	1.387	1.346	1.883	0.5
66	V350 Lac	69		1.249	2.9	1.386	1.536			0
67	IM Peg	50		1.392	11.7	1.379	1.641			0
68	TZ PsA	46		0.216	2.3	1.186	1.237			0
69	RT And	95		-0.201	0.4			1.302	1.323	1
70	SZ Psc	100		0.598	5.1			1.362	1.956	1
71	λ And	24		1.312	30.2	1.363	1.898			0
72	II Peg	29		0.828	9.1	1.363	1.870			0

$\log T_{eff}$ correspondence according to the criteria described below and indicated in the last column of Table 1. These criteria, based on data availability, are: (a) if individual (B–V) are quoted for the components, then a straightforward application of the above relation was used, (b) if the spectral type (usually of class III) of only one component along with a single value for (B–V) is given, then the observed (B–V) is assumed to correspond to this star, and (c) if two individual components are mentioned by spectral type, but only one value for (B–V) is available, we accept the spectral type classification as accurate, and adopt as each star's (B–V) and temperature the values given by Gray (1992) for that particular spectral type and luminosity class. In the absence of a reliable set of temperatures for subgiant stars we assume the temperature of luminosity class IV to be the mean between the temperatures of a dwarf and a giant star of the same spectral type. In the absence of reliable bolometric measurements for this sample we calculated bolometric luminosities (L_{bol}) from effective temperatures and radii and normalised these to the solar value. We chose the temperature scale of Gray (1992) because it is based on several studies, is therefore general, and is more appropriate for cooler stars than the Johnson scale. We do note, however, that recent work (Amado & Byrne 1996, 1997) implies that late-type stars may show a (B–V) dependence on activity itself. Any errors in T_{eff} in our sample will not effect our results significantly because most stars lie in a region where convective turnover time-scale varies slowly with T_{eff} (although differences between main-sequence and evolved stars are significant). Besides, whatever temperature scale is used, its consistent use still implies that correlation changes would be noticeable. Uncertainties in d and R yield errors in the observed surface fluxes and luminosity which would effect the correlation study. For dwarf stars and subgiant components (most of which are eclipsing) the radii should be fairly accurate. Hence we rely, as we must, on published values of d and R.

For several systems, and in particular for binaries comprised of non–eclipsing evolved components, individual masses are not given in Strassmeier et al. (1993). For those systems (noted in Table 1) we inferred the mass from the stars' positions in our HR diagram (see below). In order to test the accuracy of this method for mass determination, we compared the masses so-obtained for the whole sample to those given by Strassmeier et al. (1993) and found them to be in very good agreement (better than 0.2 $M_{\odot}$). Errors in M will also effect the results but where most of the stars lie on the HR diagram there is little difference in convective turnover time-scale for stars with mass differences of up to $0.5 M_{\odot}$. We have taken every precaution with the accuracy of the stellar parameters for this study and believe the errors are not sufficient to mask any significant changes in the correlation results.

Using our values for T_{eff} and $L/L_{\odot}$ we have plotted

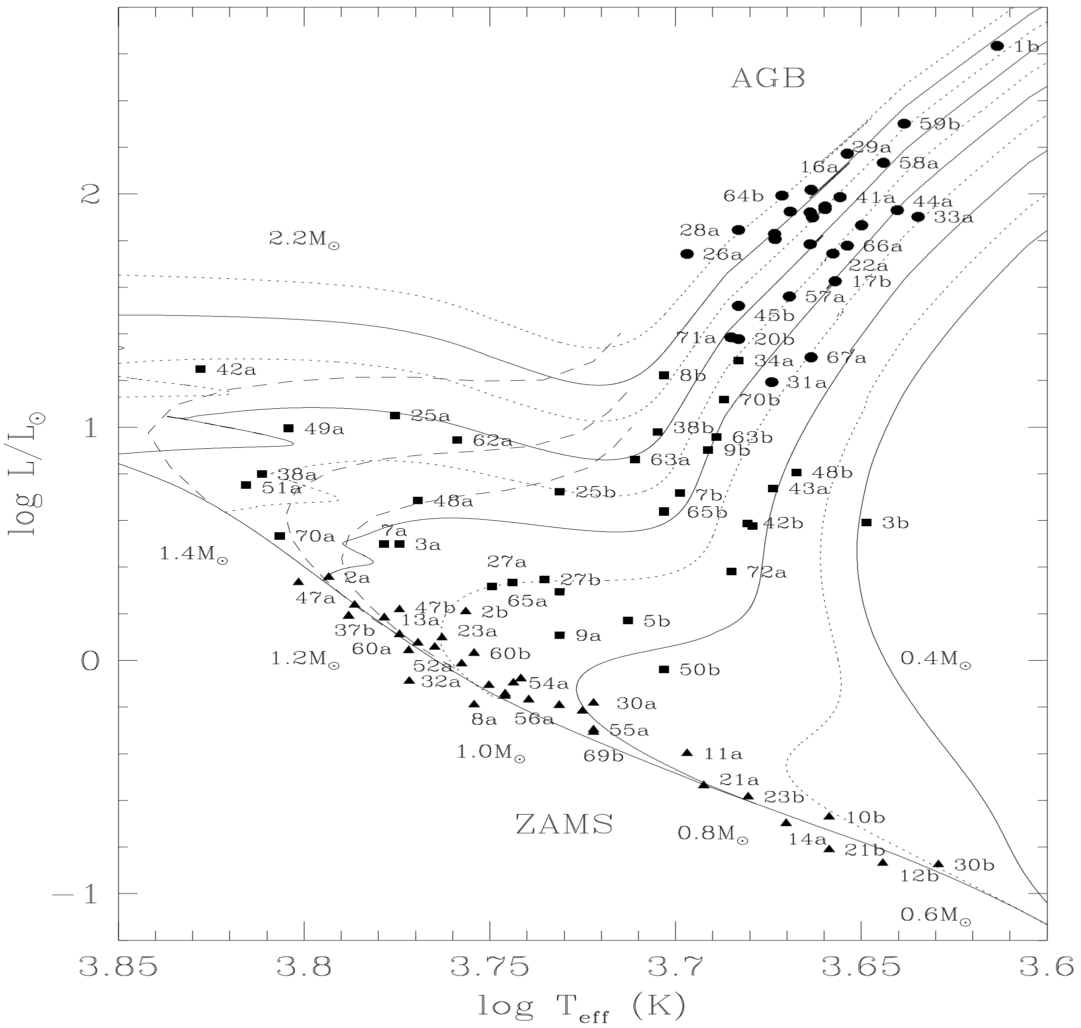

Figure 2. Hertsprung-Russell diagram showing the positions of stars in the sample (numerical codes correspond to index numbers in Tables 1 and 2; not all stars are identified). Symbols denote dwarfs (triangles), subgiants (squares) and giants (circles). Also shown are the results of the stellar models, including the ZAMS track, evolutionary tracks for stellar masses 0.4-2.2$M_{\odot}$ at steps of 0.2$M_{\odot}$ and isochrones for some higher masses (dashed lines).

in Figure 2 the position of each star in the HR diagram for this sample of active binaries. Numerical codes on this diagram correspond to the index numbers in Tables 1 and 2 and symbols are triangles for dwarf (MS) stars, squares for subgiants and circles for giants (to avoid confusion not all stars are identified). The available parameters allow us to place 103 individual stars on the HR diagram, 31 systems with both components represented, 8 systems with only hot components and 33 systems with only cool components. In Figure 2 we also show the zero-age main-sequence (ZAMS) track as well as evolutionary models for stellar masses 0.4-2.2$M_{\odot}$ (at steps of 0.2$M_{\odot}$) calculated using our evolution code (see Section 4 for details). Our HR diagram compares well with the limited study to date in this area. Popper & Ulrich (1977) plotted a small sample of active binaries in the mass-colour, mass-radius and colour-luminosity planes and concluded that they evolve from non-emission binaries as they enter the Hertzsprung gap. This is strongly suggestive that active binaries are active due to their evolutionary state. Montesinos, Giménez & Fernández-Figueroa (1988) found by comparing a sample of 22 active binaries to evolutionary models that the majority had metallicities equal to or greater than the solar value in agreement with their post-MS status. More recently Barrado et al. (1994) used a sample of 50 active binaries and found very good agreement between the ages of system components even when the luminosity classes differed. They also interpret the activity of RS CVn binaries as due to the evolution of internal structure. Our HR diagram again confirms the preponderance of active binaries in the post-MS state. As mentioned above the position of stars in the HR diagram is in general consistent with their masses and we find little evidence of incorrectly assigned temperatures or radii. The scarcity of objects in the Hertzsprung gap also gives us confidence in the parameters of this sample.

We find that the systems Z Her, RT Lac and SZ Psc

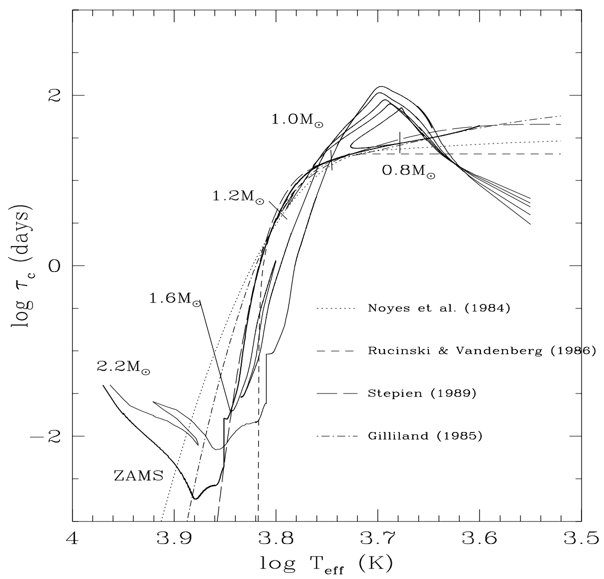

Figure 3. The behaviour of the convective turnover time-scale $\log \tau_c$ with $\log T_{eff}$ for main sequence stars and for stars with masses 0.8, 1.0, 1.2, 1.6 and $2.2M_\odot$. Changes in τ_c for stars evolving to lower temperatures are very significant. Solid lines indicate tracks calculated in the present study. For comparison the semi-empirical relationships derived by Noyes et al. (1984), Rucinski & Vandenberg (1986), Stępień (1989) and Gilliland (1985) are also shown.

show evidence, when plotted in the luminosity-temperature plane, of anisochronism. Barrado et al. (1994) also found evidence of unequal ages in Z Her and RT Lac whilst Montesinos, Giménez & Fernández-Figueroa (1988) suggested that the components of RT Lac and SZ Psc have not evolved as individual stars. Observational evidence for mass-transfer in the RT Lac system has been given by Huenemoerder (1985) and Huenemoerder & Barden (1986) whilst Hα profiles observed for the SZ Psc system by Huenemoerder & Ramsey (1984) have suggested transient periods of mass-exchange in this system. More recently Kalimeris et al. (1995) noted that the SZ Psc system is undergoing period variations of a large magnitude which may indicate the existence of an enhanced stellar wind giving rise to mass loss and/or mass transfer in this system. This may account for its anisochronic behaviour in the HR diagram. We also note the possibility of anisochronism in the 54 Cam and BH CVn systems. This again raises the question of the possibility of Algol-type evolution in some active binary systems.

4 THE STELLAR EVOLUTION CODE

For the computation of stellar structure we used the evolution code described by Eggleton (1971, 1972, 1973) and Han, Podsiadlowski & Eggleton (1994). This code solves simultaneously for structure and composition in a single implicit Newton-Raphson iterative step, includes semi-convective mixing and is appropriate for evolutionary studies up to the end of central C burning or to the He flash for high and low mass stars respectively. The code is similar to that used to study the convective zone evolution in pre-main-sequence and evolved stars by Gilliland (1985, 1986). Some significant differences between these programs are the inclusion of a better convective zone resolution in the self-adapting numerical grid of the models, the use of updated nuclear reaction rates, neutrino losses and opacities (those of Rogers & Iglesias (1992) and the low temperature molecular opacities of Weiss, Keady & Magee (1990)), an interpolative method of computing convective zone properties and the use of the refined equation of state described by Pols et al. (1995). In this code mixing length theory is treated as a diffusion process and we have set the ratio of the mixing length to the local pressure scale height, α, to 2. We refrain here from a full discussion of the methods and results of our calculations which will be described in detail in a subsequent paper (Gunn 1997). However, we stress the importance of these new calculations for the convective effects on activity in cool main-sequence and evolved stars. We also remark that the basic properties of the Sun (L, T and age) are well matched with a reasonable helium abundance of 0.28 for $z = 0.0128$ and $\alpha = 2$ using this code (Pols et al. 1995). In our models we have used the solar metallicity since this quantity is poorly known for the stars in our sample and this seems to be a reasonable assumption for most active binary systems (Montesinos, Giménez & Fernández-Figueroa 1988). Since temperature at the base of the giant branch depends rather strongly on metallicity this may not be wholly applicable to many of the more evolved systems. However, the results of our analysis are much more dependent on the accuracy of the stellar parameters. We have also assumed that the evolution of the binary components can be conveniently isolated, since, for most active binary stars in our sample, both components normally lie within their Roche surfaces (see Section 3).

In our calculations we have considered the variation of the convective turnover time-scale τ_c along the main-sequence and along evolutionary tracks for stellar masses from 0.4 to $2.2M_\odot$ at intervals of $0.1M_\odot$. This mass resolution matches the likely errors in the stellar masses. The purpose of these calculations was to provide for each of the stars in the sample a theoretical value for τ_c and hence a non-empirical Rossby number R_o. Using the position of stars in the HR diagram (see description in Section 3) we were able to infer τ_c from T, M and L. Figure 3 shows examples for certain stellar masses of the change in τ_c with temperature as stars evolve off the main-sequence. The main sequence τ_c–T relationship is also shown in this diagram and is somewhat different to the semi-empirical relationship of Noyes et al. (1984). For comparison the semi-empirical ZAMS relationship provided by Stępień (1989) and the theoretical ZAMS relationships given by Rucinski & Vandenberg (1986) and Gilliland (1985) are also shown in Figure 3. We have converted all these relationships from (B–V) to one in τ_c and T by use of the polynomial relationship between (B–V) and T for dwarf stars described in Section 3. The difference between the semi-empirical and non-empirical relationships is not surprising considering their origins. Our ZAMS model is similar to that of Gilliland (1985) for $\log T < 3.82$ and is best matched by that of Stępień (1989) for $\log T > 3.82$. A more detailed comparison between the evolutionary tracks from the present study and those of Rucinski & Vandenberg (1986) is shown in Figure 4. A broad agreement is found

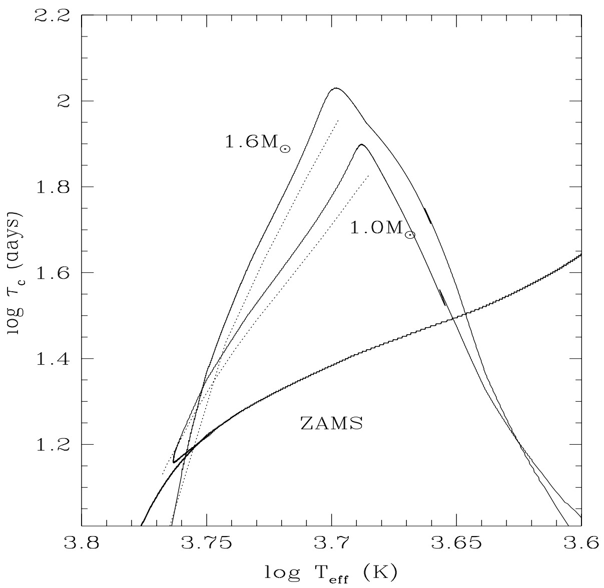

Figure 4. A detailed comparison of the behaviour of the convective turnover time-scale $\log \tau_c$ with $\log T_{eff}$ during evolution for stars of mass $1.0M_\odot$ and $1.6M_\odot$. The solid lines are tracks from the present study while dotted lines show the results of Rucinski & Vandenberg (1986). The ZAMS track from the present study is also shown. The results of the present study are in broad agreement with previous results.

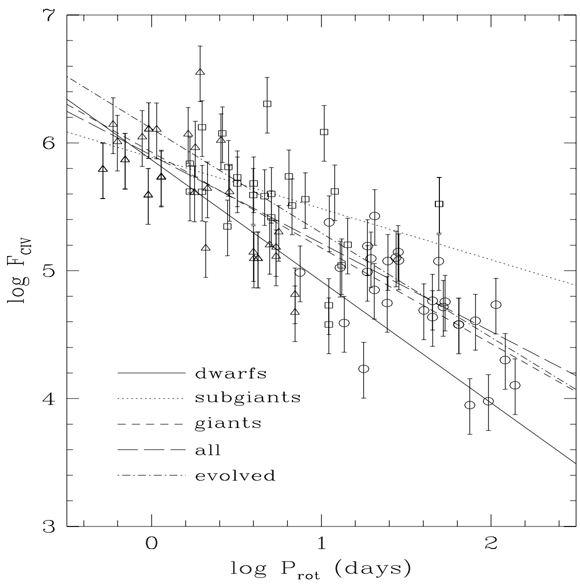

Figure 5. CIV flux, $\log F_{CIV}$, against period, $\log P_{rot}$, for the sample of active binaries in this study. The plot shows linear fits to subsets of the sample. Symbols are for dwarfs (triangles), subgiants (squares) and giants (circles).

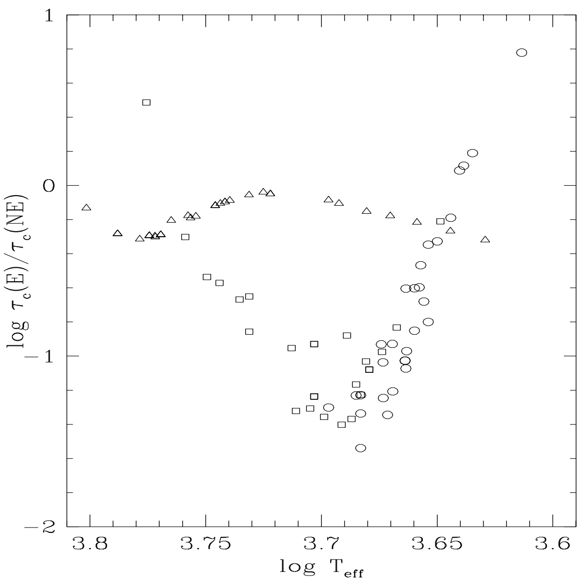

Figure 6. Values of $\log \tau_c(E)/\tau_c(NE)$ against $\log T_{eff}$ for the sample of active binaries in this study. This plot emphasises the differences between empirical and non-empirical convective turnover timescales for each luminosity class. Symbols as in Figure 5.

between the tracks although the present results show consistently higher values of τ_c.

In Figure 3 and 4 the changes in $\log \tau_c$ available for evolving stars, particularly during H-core collapse in stars with $M \geq 1.25M_\odot$ and for stars evolving across the Hertzsprung gap and towards the AGB, are quite significant. It is evident that the peak in τ_c occurs at the base of the giant branch for all stellar masses. In highly evolved stars τ_c declines with temperature with little difference between masses and forms a congruence at $\log T_{eff} \sim 3.62$. We refer the reader to Gunn (1997) for a full discussion of the implications of these effects and the differences between these and previous results. In this paper we are concerned only with a discussion of whether the CIV rotation-activity correlation improves if these evolutionary effects on convective efficiency are taken into account. Using our stellar models we ascribed to each star with the necessary parameters the non-empirical values of τ_c(NE) shown in Table 2. For comparison the empirical τ_c(E) values derived using the Noyes et al. (1984) relationship are also given in Table 2. We used convective turnover times τ_c and rotational (in fact orbital) periods P_{rot} to compute empirical and non-empirical Rossby numbers. The available parameters allowed us to derive τ_c for 87 individual stars, 15 systems with both components represented, 34 systems with only hot components and 23 with only cool components. This sample then comprises of 32 dwarf stars, 26 subgiants and 29 giants.

5 RESULTS

In Figure 5 we plot the logarithm of the CIV surface flux, $\log F_{CIV}$ against $\log P_{rot}$ for our sample of active binaries. There is a strong correlation of activity level as measured by CIV flux with rotation period. We also show linear fits to the data separately for dwarfs, subgiants and giants, evolved components only and the entire data set. The scatter in the diagram is such that it is not possible to attach any significance to the different slopes of the fits for each luminosity class. All classes do, however, appear to show a good degree of correlation. A summary of the linear fits

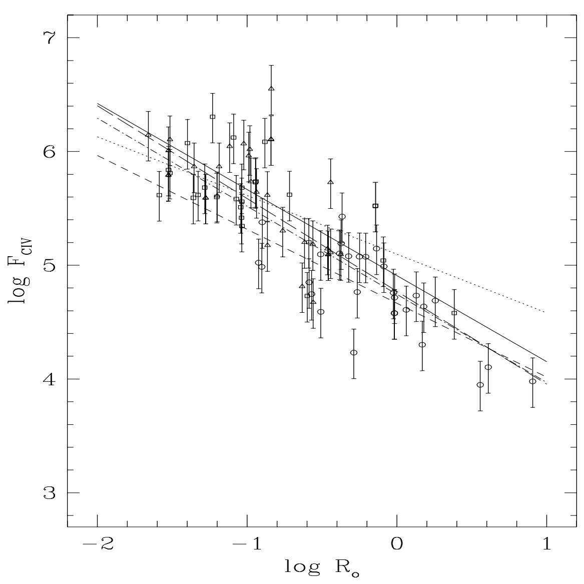

Figure 7. CIV flux, $\log F_{CIV}$, against Rossby number, $\log R_o$, derived from our evolutionary models of τ_c, for the sample of active binaries in this study. Linear fits are shown for subsets of the sample. Symbols as in Figure 5.

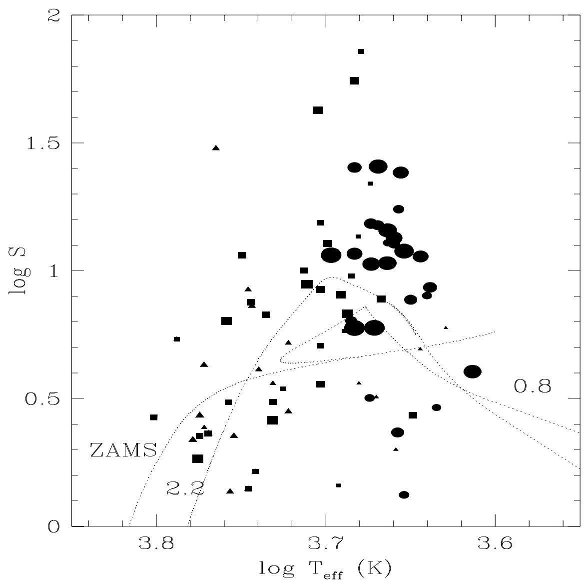

Figure 8. The normalised activity parameter $\log S$ (see text) for each star in our sample plotted against $\log T_{eff}$. Symbols as in Figure 5, their size proportional to mass. Also shown is the (arbitrary) position of the ZAMS track and evolutionary models of τ_c for masses of $0.8M_\odot$ and $2.2M_\odot$ (see text).

and correlation coefficients for each luminosity group for log P, log R_o(E) (empirical) and log R_o(NE) (non-empirical) is shown in Table 3. Simon & Fekel (1987) have provided a detailed investigation of rotation-activity correlations using several UV emission lines, including CIV, for both single and binary stars of different luminosity classes. They found $\log F_{CIV} = 5.91 - 1.34 \log P_{rot}$ for single dwarf stars with $P_{rot} \geq 2$ days, $\log F_{CIV} = 5.69 - 0.44 \log P_{rot}$ for giants in binary systems and $\log F_{CIV} = 6.05 - 0.64 \log P_{rot}$ for all luminosity classes in binary systems. The stronger dependence on $\log P_{rot}$ for single stars is suggestive of additional factors on activity for evolved binary stars. We note that our results for all binary systems ($\log F_{CIV} = 5.902 - 0.69 \log P_{rot}$) is very similar to these previous results but, surprisingly, with a sample size almost 2.5 times bigger, we find a decrease in correlation from -0.860 to -0.806. Our results for giant stars show a greater dependence on $\log P_{rot}$ than previous results and a slightly improved correlation coefficient (-0.510 to -0.589). Montesinos & Jordan (1988) also examined the F_{CIV}–P_{rot} correlation and found for dwarfs that $\log F_{CIV} \propto -1.22 \log P_{rot}$ which is closer to our value than that of Simon & Fekel (1987). However, both the Simon & Fekel (1987) and Montesinos & Jordan (1988) samples are dominated by single dwarf stars as opposed to binary dwarfs.

Figure 6 shows $\log \tau_c(E)/\tau_c(NE)$ against $\log T_{eff}$ for the stars in our sample. For dwarf stars the differences in τ_c are small along most of the main sequence, never exceeding about 0.3 dex. For giants and subgiants the differences are much more significant, reaching about 1.6 dex at the base of the AGB. The small difference for dwarf stars results in little change in correlation for this subsample.

In Figure 7 we show the CIV surface flux, $\log F_{CIV}$ against non-empirical values of the Rossby number $\log R_o$. The data again show a high degree of correlation as expected but the linear fits (see Table 3) do not differ significantly between the luminosity classes. We note that the lowest degree of correlation is found for subgiant components. Although the empirical Rossby numbers should be meaningless for evolved components we do note an increase in correlation when using non-empirical values. A similar decrease in correlation is, however, seen in dwarf components so the improvement for evolved stars cannot be claimed to be significant. This is opposite to the results of Simon & Fekel (1987) who found no correlation between UV emission and Rossby numbers for active giants. However, their Rossby numbers were predicted qualitatively from the limited modelling of Gilliland (1985). In our results there are some indications that the use of Rossby number is preferable to rotation period and that non-empirical values are preferable to the empirical values of Noyes et al. (1984). These results are surprising considering the differences between empirical and non-empirical Rossby numbers for the evolved components. We note that systems in our sample showing comparatively high CIV flux values are UX Ari, V711 Tau, σ Gem, BH CVn, TZ CrB, AR Lac, IM Peg and λ And. Many of these are already known to be highly active binary systems.

We have attempted to interpret these results by assigning to each star in the sample a normalised activity parameter S such that

$$S = \frac{F\Omega_o}{F_o\Omega} \propto \frac{\tau_c}{\tau_{c_o}}, \qquad (1)$$

where Ω is rotation rate, F is the CIV flux and the 'o' subscript refers to the values for some arbitrary star in the sample. Thus S will have the same functional form as $\log \tau_c$. We have used the highly active star HR 1099 as our reference and show in Figure 8 the normalised activity parameter $\log S$ plotted against $\log T_{eff}$ for all stars in our sample. As usual symbols denote luminosity class and the symbol sizes represent the stellar mass of the component. In order to compare

Table 3. Results of linear fits between CIV λ1550 surface flux, $\log F_{CIV}$, and $\log P_{rot}$, $\log R_o$(E) and $\log R_o$(NE) for luminosity subsets of the sample. For each fit we show the number of points in the sample n, the gradient a, constant b and correlation coefficient r.

		$\log P$			$\log R_o$(E)			$\log R_o$(NE)		
Group	n	a	b	r	a	b	r	a	b	r
dwarfs	32	-0.950	5.866	-0.696	-0.717	5.003	-0.631	-0.757	4.910	-0.607
subgiants	26	-0.400	5.886	-0.546	-0.490	5.315	-0.533	-0.516	5.097	-0.570
giants	29	-0.750	5.928	-0.589	-0.742	4.892	-0.596	-0.650	4.666	-0.663
evolved	55	-0.817	6.111	-0.775	-0.860	5.007	-0.796	-0.775	4.744	-0.831
all	87	-0.690	5.902	-0.806	-0.775	4.997	-0.808	-0.816	4.770	-0.791

with the expected trend we assume that the $\log S$ - $\log \tau_c$ relation is indeed linear and scale our main-sequence $\log \tau_c$ - $\log T_{eff}$ relationship by fitting the linear part of the curve (in the range $3.64 \leq \log T_{eff} \leq 3.74$) to the main-sequence points in the $\log S$ - $\log T_{eff}$ plane. We similarly show in Figure 8 scaled curves for stellar masses of 2.2 and $0.8 M_{\odot}$. Although these scalings do not represent an exact correspondence between $\log S$ and $\log \tau_c$ this diagram reveals an interesting feature of the observational data; the normalised activity parameter is not linearly commensurate with stellar mass as we would expect from the stellar models. We expect to see a clear distinction of masses for evolved stars in the $\log S$ - $\log T_{eff}$ plane. Thus, in contrast to the theoretical predictions of convective zone evolution for stars of different masses, activity as measured by CIV surface flux appears to be only weakly related to mass. Although the position of the peak $\log S$ for evolved stars does appear to be broadly consistent with the models, Figure 8 implies the existence of either errors in our assumptions and/or system parameters or an additional factor other than rotation and convective motion influencing the levels of activity in evolved active stars.

We also considered whether the subtraction of a 'basal' CIV flux from our sample affected the degree of correlation. We estimated CIV basal flux for each star using (B–V) colour and data provided by Rutten et al. (1991) but found them to be 2-3 orders of magnitude less than the observed values and hence insignificant in the correlation analysis. We note that Schrijver (1987) does not find evidence for the existence of a basal flux level in the CIV line in late-type stars. We further investigated the possibility of a gravity dependence in the correlation. For each star we calculated surface gravity (normalised to solar) and derived correlation coefficients for functions of the form $\log F = a_0 + a_1 \log P + a_2 \log g$. We find that for the entire sample there is no significant change in correlation although a noticeable increase for the non-empirical Rossby number is found. For the sample of evolved stars there is no significant change in correlation. Interestingly we find a 5-10% increase in correlation for dwarf stars. Although in some instances there is some evidence of improved correlation using an additional gravity term the dispersion in the results renders them inconclusive. The gravity dependence results are interesting in that they show a fairly consistent increase in correlation for P to $R_o(E)$ to $R_o(NE)$ which is not shown in the simpler relationship. We note that the proposed g dependence of the rotation-activity correlation seen in the CIV line by Montesinos & Jordan (1988) for evolved stars is not apparent in our data. As discussed by Jordan & Montesinos (1991) the difference between dwarf and evolved stars is probably not simply due to surface gravity.

We have discussed the observational errors and the errors in the stellar parameters elsewhere in this paper. We conclude that these are small so that the lack of improvement in correlations which we present are evidence for additional factors in the connection between rotation, convection and activity. Below we discuss some possibilities for these additional factors.

6 DISCUSSION

The above results cause us to speculate on the possibility of effects on activity which have not previously been considered in detail. The application of dynamo theory in cool stars is sufficiently uncertain that the Rossby number may not be the best single parameter to describe the dynamo action. If dynamo theory were essentially correct the magnetic field generation and hence the release of magnetic energy in the form of chromospheric heating etc. should depend only on atmospheric structure (or spectral/luminosity class) and rotation rate. In mean-field dynamo theories a minimum constraint for the amplification of magnetic fields is given by the dynamo number N_d (Parker 1979),

$$N_d = \frac{\alpha \Omega' d^4}{\eta^2} \tag{2}$$

where α is the product of mean convective helicity and the convective turnover time, Ω' is the radial gradient of angular velocity across the convection zone, d is the characteristic length scale of convection and η is a turbulent magnetic diffusivity. Durney, Mihalas & Robinson (1981), Durney & Robinson (1982) and Robinson & Durney (1982) provide convincing arguments that N_d is the relevant parameter describing dynamo efficiency. Making some assumptions about the form of α and Ω', Hartmann & Noyes (1987) point out that,

$$N_d \sim R_o^{-2} \tag{3}$$

where R_o is the classical Rossby number (P_{rot}/τ_c). However, this characterisation of the dynamo effect suffers from several fundamental assumptions.

Firstly, calculations of τ_c are performed one pressure scale height above the base of the convection zone. This is chosen because in higher regions buoyancy mechanisms act too quickly to allow significant field amplification and in the stable region just below the convective boundary fields are maintained for time-scales inconsistent with observed cycle periods. However, the actual zone across which the dynamo is operating is not known and, since τ_c is strongly depth dependent, this could significantly alter these simple models. The possibility that the dynamo is rooted in quite different parts of the convection zone for stars of different mass and age has not yet been investigated.

Secondly, in the usual formulation of mixing length theory used to describe the stellar interior convection, the ratio of mixing length to pressure scale height, l/H, also often called α, is essentially a free parameter. Calibration of α is possible only with helioseismological studies of the Sun which directly measure the depth of the convection zone (Gough 1986). Rucinski & Vandenberg (1986) used a value of $\alpha = 1.6$ in computing stellar convective envelopes because derived isochrones based on this value best reproduce the observed colour-magnitude diagrams for globular clusters with wide-ranging age and composition (Vandenberg 1983, 1984). Using a standard mass-colour relationship Noyes et al. (1984) used an iterative fitting procedure to the models of Gilman (1980) and found that observational data were best described by $\alpha = 1.9$. Gilliland (1985) showed that different colour-temperature relations require quite different values of α necessary to reproduce the Noyes et al. (1984) relationship. Although various studies to date place α in the range 1.5–2.0 we have used $\alpha = 2.0$ since small changes in this parameter do not cause significant departures from the log τ_c-log T_{eff} evolution shown in Figure 3. Nevertheless, the uncertainty in the formulation of mixing length theory, and in particular the value of α, may affect our ability to derive adequate rotation-activity relations for evolved stars.

Thirdly, the classical Rossby number involves the use of surface rotation rate (or in fact orbital period in the case of close binaries) and therefore does not take account of the radial differential rotation required to produce the dynamo. This arises because of the assumption that Ω' is proportional to Ω/d for which there is no firm theoretical basis. The fact remains that we do not know the form of the angular velocity-depth profile for any star and certainly cannot predict its evolution. Based on data obtained by Duval et al. (1984), Durney (1985) found that in the Sun the shear in angular velocity is proportional to the surface angular velocity. In contrast, some of the solar results of Brown et al. (1989) imply that the angular velocity-depth profile in stars may be dependent on spectral type but have little or no dependence on surface rotation. Obviously the use of R_o is extremely questionable if we cannot be sure of the shear dependence on P_{rot} or otherwise. We suggest that one factor which may be important, particularly for the evolving systems, is the dredging of angular momentum from the core to the envelope which may alter the angular velocity-depth profile (Pinsonneault et al. 1989; Simon & Drake 1989). The non-linear dependence of S on mass may be implying that evolved stars can have very different angular velocity-depth profiles. The very rapid variation in internal structure also poses the question of whether an efficient dynamo can operate, be maintained and be simply parametrised.

This point also leads us to a discussion of the effects of binarity on stellar activity, since our sample of evolved stars are all members of close binary systems. Young & Koniges (1977) noted that giants in binary systems with circular orbits appear to show enhanced chromospheric emission in the CaII lines. Strassmeier et al. (1989) also noted a similar effect; Hα and CaII emissions from giant stars in binary systems display higher activity levels than dwarf stars of the same rotation rate. Active close binaries also appear to be more active than single stars (with similar properties) in the radio (Gibson 1980) and X-ray regimes (Rutten 1987). Based on a study of synchronised binaries Basri, Laurent & Walter (1985) concluded that enhanced activity in these stars may be caused by either their evolutionary state or tidal effects. Basri (1987), Strassmeier et al. (1990) and Dempsey et al. (1993) have all concluded that binarity itself is not a strong factor in determining activity levels but is important in its ability to induce and maintain high rotation rates. However, more recently, de Medeiros & Mayor (1995) found, from studying X-ray fluxes, that orbital circularisation was necessary for enhanced emission. In close binaries the effects of mass transfer could also have an effect on activity; Young & Koniges (1977) suggest that another relevant parameter for activity studies in binaries is the ratio of the stellar to the Roche radius. We conclude that the binarity of the stars in our sample may affect activity levels, either by mass transfer effects or, more likely, tidal effects on the normal operation of the stellar dynamo; perhaps by altering the angular velocity-depth profile. In order to address this problem a study of single evolved active stars is required.

We should also address the possibility of a different manifestation of magnetic activity in evolved stars even if the dynamo description is essentially correct. Jordan & Montesinos (1991) studied the dependence of *coronal* temperatures and emission measures on Rossby numbers and found that the dynamo number, $N_d = (R_c/H_p)^{0.5} R_o^{-1}$, where R_c is the radius and H_p the pressure scale-height at the base of the convection zone, produced a better agreement between correlations for dwarfs and subgiants. In addition they found that the correlations involved a small gravity dependence. Montesinos & Jordan (1993) also investigated this gravity dependence. However, on the basis that $(R_c/H_p)^{-0.5} \sim 1$ for evolved stars they point out that R_o provides as good a correlation as N_d for active binary systems, but that N_d seems to give better agreement when considering a mixture of dwarfs and evolved stars. Nevertheless, much of the work in this area presupposes a unique dependence of photospheric fields B_s on R_o or that $B_s f_s$, where f_s is the filling factor, depends on R_o. If we assume conservation of magnetic flux as a flux tube is transported to the stellar surface then we can write the photospheric field as

$$B_s = B_{cz} \left(\frac{L}{2R_{ph}} \right)^2 \tag{4}$$

where B_{cz} is the field strength at the base of the convection zone, R_{ph} is the radius of the magnetic flux tube at the photosphere and L is the pressure scale height. But if we further assume equipartition the pressure outside the flux tube, the photospheric pressure P_g, constrains B_s such that $B_s \sim \sqrt{8\pi P_g}$. Even in this simplified view it is clear that stellar luminosity or evolutionary state can determine to some extent the B–R_o dependence and hence rotation-activity correlations for many active stars. As discussed we have found no conclusive evidence for gravity dependence in our data.

We also draw attention to the fact that the activity indicator units could mask correlations with rotation. Surface fluxes may well indicate the effects of individual flux tubes and eliminate the stellar radius dependence while total luminosity may refer to the total number of such flux tubes. Hence the choice of units relies on our belief that local structures in stars of different surface gravities are similar. Schrijver, Mewe & Walter (1984) suggest an inherent difference in the coronal temperatures and loop structures between dwarfs and giants while Gunn, Doyle & Houdebine (1997) suggest dwarfs and giants show different manifestations of activity in the form of plage-like and prominence-like features respectively. Basri (1987), however, found that activity structures are similar on all stars. In this study we therefore chose to use surface flux. Although this topic has received a lot of attention in the literature we refrain from a full discussion here.

This work would benefit from further development. A full deduction of any additional factors involved in the connection between rotation, convection and activity in late-type stars requires analyses of samples of single evolved stars and unevolved close binaries in an attempt to disentangle the effects of evolution and binarity. All such studies require better sets of stellar parameters, particularly distances which may be available from the forthcoming Hipparchos results. Although already complex, there is scope for improvement of stellar convection models using mixing-length theory, the details of dynamo generation of magnetic fields and the manifestation of those fields in stars of different spectral type and gravity. Further investigation of the applicability of R_o, or alternatively N_d, in such studies is also required. We believe an area requiring immediate attention is the question of the form of the angular velocity-depth profile and its effects on dynamo activity in late-type stars.

7 CONCLUSIONS

We have investigated the rotation-activity correlations using IUE SWP measurements of the CIV emission line at 1550Åfor a sample of 72 active binary systems. We characterise the stellar dynamo efficiency with a non-empirical Rossby number derived from stellar evolution models. For all luminosity classes a distinct correlation exists but no significant improvement of the correlations was found when using non-empirical as opposed to empirical Rossby numbers for main-sequence stars. We have further found that activity in evolved stars does not appear to be linearly commensurate with mass as expected from the stellar models and shows no significant dependence on surface gravity. Without knowledge of the radial differential velocity gradients in active stars the study of rotation-activity correlations using the classical Rossby number is perhaps unwarranted. We believe this, in addition to the unknown effects of binarity and surface gravity, and errors in the stellar parameters, are responsible for the lack of improvement in correlation. This study therefore highlights the limitation of current dynamo models when applied to evolved active stars.

ACKNOWLEDGEMENTS

Research at Armagh Observatory is grant aided by the Dept. of Education for N. Ireland. We also acknowledge the computer support by the STARLINK project funded by the UK PPARC. This research has, in part, made use of the Simbad database operated at CDS, Strasbourg, France. CKM acknowledges support by a joint UK/Greek research program in astronomical science (ATH/882/2/ASTRO) and by the Greek Ministry of Industry, Research and Technology PENED Program (70/3/2811). AGG would like to thank Armagh Observatory for a research scholarship and several travel grants during the period of this work. AGG is indebted to P. P. Eggleton for his invaluable assistance and hospitality during the modification of the stellar evolution code for this research.

REFERENCES

Amado P. J., Byrne P. B., 1996, Irish Astron. J. 23, 177
Amado P. J., Byrne P. B., 1997, A&A 319, 967
Barrado D., Fernàndez-Figueroa M. J., Montesinos B., De Castro E., 1994, A&A 290, 137
Basri G., 1987, ApJ 316, 377
Basri G., Laurent R., Walter F. M., 1985, ApJ 298, 761
Brown T. M., Christensen-Dalsgaard J., Dziembowski W. A., Goode P., Gough D. O., Morrow C. A., 1989, ApJ 343, 526
Bruner M. E., McWhirter R. W. P., 1988, ApJ 326, 1002
Cayrel de Strobel G., Cayrel R, Friel E., Zahn J. -P., Bentolila C., 1994, A&A 291, 505
de Medeiros J. R., Mayor M., 1995, A&A 302, 745
Dempsey R. C., Linsky J. L., Fleming T. A., Schmitt J. H. M. M., 1993, ApJS 86, 599
Donati J. -F., Henry G. W., Hall D. S., 1994, A&A 293, 107
Doyle J. G., 1996a, A&A 307, 162
Doyle J. G., 1996b, A&A 307, L45
Drake S. A., Simon T., Linsky J. L., 1989, ApJS 71, 905
Durney B. R., 1985, ApJ 297, 787
Durney B. R., Latour J., 1978, *Geophys. Astrophys. Fluid Dyn.* 9, 241
Durney B. R., Mihalas D., Robinson R. D., 1981, PASP 93, 537
Durney B. R., Robinson R. D., 1982, ApJ 253, 290
Duval P. L., Dziembowski W. A., Goode P. R., Gough D. O., Harvey J. W., Leibacher J. W., 1984, Nat 310, 22
Eggleton P. P., 1971, MNRAS 151, 351
Eggleton P. P., 1972, MNRAS 156, 361
Eggleton P. P., 1973, MNRAS 163, 279
Fekel F. C., Mofett T. J., Henry G. W., 1986, ApJS 60, 551
Gibson D. M., 1980, in Plavec M. J., Ulrich R. K., eds, Proc. IAU Symp. 88, Close Binary Stars: Observations and Interpretation. Reidel:Dordrecht, p.31
Giddings J., Rees P., Mills D., Clayton M., 1996, IUEDR - IUE Data Reduction Package, STARLINK User Note 37.11
Gilliland R. L., 1985, ApJ 299, 286
Gilliland R. L., 1986, ApJ 300, 339
Gilman P. A., 1980, in Gray D. F., Linsky J. L., eds, Proc. IAU Coll. 51, Stellar Turbulence. Springer-Verlag, Berlin, p.19
Gough D. O., 1986, in Gough D. O., ed, Seismology of the Sun and Distant Stars. Reidel:Dordrecht, p.287
Gray D. F., 1992, The Observation and Analysis of Stellar Photospheres. Cambridge Univ. Press, Cambridge

Gunn A. G., 1996, Irish Astron. J. 23, 33
Gunn A. G., 1997, (in preparation)
Gunn A. G., Doyle J. G., Houdebine E. R., 1997, A&A 319, 211
Han Z., Podsiadlowski P., Eggleton P. P., 1994, MNRAS 270, 121
Hartmann L., Baliunas S. L., Duncan D. K., Noyes R. W., 1984, ApJ 279, 778
Hartmann L. W., Noyes R. W., 1987, ARA&A 25, 271
Hempelmann A., Schmitt J. H. M. M., Schultz M., Rüdiger G., Stępień K., 1995, A&A 294, 515
Howarth I. D., Murray J., Berry D. S., 1996, DIPSO - A Friendly Spectrum Analysis Program, STARLINK User Note 50.19
Houdebine E. R., Mathioudakis M., Doyle J. G., Foing B. H., 1996, A&A 305, 209
Huenemoerder D. P., 1985, AJ 90, 499
Huenemoerder D. P., Barden S. C., 1986, AJ 91, 583
Huenemoerder D. P., Ramsay L. W., 1984, AJ 89, 549
Jordan C., Montesinos B., 1991, MNRAS 252, 21P
Kalimeris A., Mitrou C. K., Doyle J. G., Antonopolou E., Rovithis-Livaniou H., 1995, A&A 293, 371
Kim Y. -C., Demarque P., 1996, ApJ 457, 340
Kraft R. P., 1967, ApJ 150, 551
Linsky J. L., 1983, in Baliunas S., Hartmann L. W., eds, Cool Stars, Stellar Systems and the Sun. Springer Verlag, p.244
Middelkoop F., 1981, A&A 101, 551
Montesinos B., Giménez A., Fernández-Figueroa M. J., 1988, MNRAS 232, 361
Montesinos B., Jordan C., 1993, MNRAS 264, 900
Montesinos B., Jordan C., 1988, in A Decade of UV Astronomy with IUE, ESA SP-281, Vol. 1, p.283
Noyes R. W., 1983, in Stenflo J. O., ed, Proc. IAU Symp. 102, Solar and Stellar Magnetic Fields: Origins and Coronal Effects. Reidel:Dordrecht, p.133
Noyes R. W., Hartmann L., Baliunas S., Duncan D., Vaughan A. H., 1984, ApJ 279, 763
Oranje B. J., Zwaan C., Middelkoop F., 1982, A&A 110, 130
Pallavicini R., Golub L., Rosner R., Vaiana G. S., Ayres T., Linsky J. L., 1981, ApJ 248, 279
Parker E. N., 1970, ARA&A 8, 1
Parker E. N., 1977, ARA&A 15, 45
Parker E. N., 1979, Cosmical Magnetic Fields. Clarendon Press, Oxford
Pinsonneault M. H., Kawaler S. D., Sofia S., Demarque P., 1989, ApJ 338, 424
Pols O. R., Tout C. A., Eggleton P. P., Han, Z., 1995, MNRAS 274, 964
Popper D. M., Ulrich R. K., 1977, ApJ 212, L131
Robinson R. D., Durney B. R., 1982, A&A 108, 322
Rogers F. J., Iglesias C. A., 1992, ApJS 79, 507
Rucinski S. M., Vandenberg D. A., 1986, PASP 98, 669
Rutten R. G. M., 1987, A&A 177, 131
Rutten R. G. M., Schrijver C. J., 1987, A&A 177, 155
Rutten R. G. M., Schrijver C. J., Lemmens A. F. P., Zwaan C., 1991, A&A 252, 203
Schrijver C. J., Mewe R., Walter F. M., 1984, A&A 138, 258
Schrijver C. J., 1987, A&A 172, 111
Simon T., Fekel F. C., 1987, ApJ 316, 434
Simon T., Drake S. A., 1989, ApJ 346, 303
Singh K. P., Drake S. A., White N. E., 1996, AJ 111, 2415
Skumanich A., 1972, ApJ 171, 565
Slee O. B. et al., 1987, MNRAS 229, 659
Stępień K., 1989, A&A 210, 273
Stępień K., 1994, A&A 292, 191
Strassmeier K. G., Fekel F. C., Bopp B. W., Dempsey R. C., Henry G. W., 1990, ApJS 72, 191
Strassmeier K. G., Hall D. S., Boyd L. J., Genet R. M., 1989, ApJS 69, 141
Strassmeier K. G., Hall D. S., Fekel F. C., Scheck M., 1993, A&AS 100, 173
Tan H., Wang X., Pan K., 1991, Chin. A&A 15, 461
Vandenberg D. A., 1983, ApJS 51, 29
Vandenberg D. A., 1984, Maeder A., Renzini A., eds, Observational Tests of the Stellar Evolution Theory. Reidel:Dordrecht, p.143
Vilhu O., 1984, A&A 133, 117
Vilhu O., Rucinski S. M., 1983, A&A 127, 5
Walter F. M., 1981, ApJ 245, 677
Walter F. M., Bowyer S., 1981, ApJ 245, 671
Weiss A., Keady J. J., Magee N. H., 1990, At. Data Nucl. Data Tables, 45, 209
Wilson O. C., 1963, ApJ 138, 832
Young A., Koniges A., 1977, ApJ 211, 836