THE ASTROPHYSICAL JOURNAL, **248**:279–290, 1981 August 15

RELATIONS AMONG STELLAR X-RAY EMISSION OBSERVED FROM *EINSTEIN*, STELLAR ROTATION AND BOLOMETRIC LUMINOSITY

R. PALLAVICINI,[1] L. GOLUB, R. ROSNER, AND G. S. VAIANA[2]
Harvard-Smithsonian Center for Astrophysics
T. AYRES[3]
Laboratory for Atmospheric and Space Physics
AND
J. L. LINSKY[3, 4]
Joint Institute for Laboratory Astrophysics
Received 1980 December 9; accepted 1981 February 12

ABSTRACT

We have determined the correlation between observed stellar X-ray luminosities, bolometric luminosities, and projected rotational velocities $v \sin i$ for stars of various spectral types and luminosity classes observed by the *Einstein* Observatory. There are two clearly defined patterns of behavior observed. Early type stars (O3–A5) have X-ray luminosities which are proportional to bolometric luminosity. The proportionality constant is $(1.4 \pm 0.3) \times 10^{-7}$ and is independent of luminosity class. In contrast, late type stars (G to M) have X-ray luminosities strongly dependent on rotation rate $[L_x \sim (v \sin i)^{1.9 \pm 0.5}]$ and independent of bolometric luminosity; this relation for late type stars is again found to be independent of luminosity class. This dependence is equivalent to a relation $f_x \sim \Omega^2$ between the X-ray surface flux and the stellar angular velocity. F stars as a class are intermediate, having X-ray luminosities substantially higher than would be predicted on the basis of the early type star L_x–L_{bol} relation, but substantially lower than expected from the late type velocity dependence. The location of RS CVn stars as a class is discussed with respect to the dependence of X-ray luminosity on rotation.

Subject headings: stars: coronae — stars: rotation — X-rays: sources

I. INTRODUCTION

X-ray observations from the *Einstein* Observatory have for the first time demonstrated the pervasiveness of the coronal phenomenon in stars (Vaiana *et al.* 1981). We now know that X-ray emission from stars is the norm and that almost all stars, with the possible exception of very late type giants and supergiants (Ayres *et al.* 1981), have been detected as X-ray sources. At the same time, Vaiana *et al.* (1981) noted that within each spectral type a broad range of X-ray luminosity levels was observed; the range within each spectral type is typically two to three orders of magnitude, except for F stars, which have a more sharply peaked luminosity function.

For early type stars there is evidence of a correlation between X-ray emission and bolometric luminosity. Harnden *et al.* (1979) reported the constancy of the X-ray to V-band luminosity ratio for a sample of six early O-type stars; since all of the stars in this sample had nearly the same color, the relationship is equivalent to one having a constant X-ray to bolometric luminosity ratio. Long and White (1980) reported a strong correlation between X-ray and bolometric luminosities for a sample of 16 stars ranging from O4 through B9, with L_x ranging from 10^{-6} to 10^{-8} of L_{bol}.

In the following, we will determine the range of spectral types for which the above rule holds, finding that it extends from O4 through A9 using 35 stars total, and is independent of luminosity class, i.e., independent of gravity at fixed T_{eff}.

Among various parameters which may be relevant for chromospheric and coronal emission in late type stars, there are several lines of evidence, both observational and theoretical, which suggest *rotation* as a prominent factor (Vaiana 1980*b*; Linsky 1980). For instance, early statistical work on Ca II emission (Wilson 1966; Kraft 1967*a*; Skumanich 1972) has shown that the level of

[1] Also Osservatorio Astrofisico di Arcetri, Firenze, Italy.
[2] Also Osservatorio Astronomico di Palermo, Italy.
[3] Guest Observer with the *Einstein* Observatory.
[4] Staff Member, Quantum Physics Division, National Bureau of Standards.

chromospheric emission is related to rotation and age. This is further supported by the more detailed finding that some well-known, young, fast-rotating single stars, such as π^1 UMa and EQ Vir, appear to have stronger than average chromospheric (Linksy *et al.* 1979), as well as coronal emission (Vaiana *et al.* 1981). Further, the strong difference in chromospheric and transition region emission between the primary and secondary stars of the spectroscopic binary α Aur has been interpreted as due to the different rotation rate of the two components (Ayres and Linsky 1980). Enhanced rotation in close binary systems, which are forced to synchronism by tidal interaction, may be responsible for the enhanced chromospheric and coronal emission of RS CVn stars (Walter, Charles, and Bowyer 1980; Walter and Bowyer 1981). Johnson (1981) finds no trend in rotation versus L_x for three slowly rotating late type stars, but his data are included in our present study. Finally, indications exist that the so-called BY Dra syndrome in dMe stars may be principally due to rotation (Bopp and Fekel 1977; Bopp and Espenak 1977).

The observational indications mentioned above are further supported by theoretical arguments and by the solar analogy. In the solar case, coronal emission (Vaiana and Rosner 1978) as well as chromospheric emission (Zwaan 1977), are largely determined by magnetic fields, which in turn are considered to be continuously generated by a dynamo action involving the interaction of rotation and convection (see, for example, Tassoul 1978, Parker 1979). If convection and dynamo-generated magnetic fields are common to all late type stars and if the level of chromospheric and coronal emission in stars is related to magnetic fields as it is for the Sun, then rotation should be expected to be an important parameter (Vaiana 1980*a*, *b*, *c*; Rosner 1980; Linsky 1980).

It is possible that rotation may also be important for X-ray emission of early type stars. It certainly plays a role in such phenomena as Be stars (Slettebak 1976), and in other stars for which the reduction of effective gravity due to rapid rotation also affects mass losses and stellar wind generation (Conti 1978; Cassinelli 1979; Lamers 1981). More generally, rotation may be important as a source of nonthermal energy which may be used for the heating of stellar coronae (Thomas 1981), possibly through the interaction of primordial fields with surface turbulence induced by rotational instabilities (Vaiana *et al.* 1981).

It is our purpose in this paper to explore the relationship between stellar X-ray emission and stellar rotation throughout the H-R diagram by using X-ray observations from the *Einstein* Observatory and published data on rotational velocities. In the next section we present the data; in § III we discuss the results of the correlation for stars of different spectral types and luminosity classes, and finally, in § IV we discuss the implications for mechanisms for coronal formation.

II. THE DATA

a) *X-ray Observations*

The X-ray data used in this paper are all from the *Einstein* Observatory. Most of the data are from the Center for Astrophysics (CfA) stellar survey program and collaborators (Vaiana *et al.* 1981), supplemented by additional published data on early type stars from the Columbia group survey (Long and White 1980), from the guest observer programs of Ayres and Linsky, and by recent, as yet unpublished, data from the CfA survey, as well as unpublished data kindly provided to us by Guest Observer J. Cassinelli. For purposes of comparison, we have also used results for RS CVn stars from Walter and Bowyer (1981). Most of the data have been obtained with the Imaging Proportional Counter (IPC), a position-sensitive X-ray detector at the focus of the *Einstein* Observatory (*HEAO 2*). The instrument and data reduction techniques have been fully described by Giacconi *et al.* (1979). Details on X-ray source location, optical identification and other relevant data can be found in Vaiana *et al.* (1981) and Long and White (1980). The X-ray luminosities derived from IPC measurements are estimated to have uncertainties of the order of $\sim$20% due to gain variations and uncertainties in the channel boundaries.

For visual binary systems not resolved by the IPC, the observed X-ray luminosity refers to the total emission from the system. When ambiguity is present, we have considered both components (when possible), but we have treated the total X-ray luminosity as an upper limit. For binary systems formed by stars of similar spectral types, the total X-ray flux has been split equally between the two components. For multiple systems resolved by the High Resolution Imager (HRI), the X-ray luminosity refers to the individual components in the system and no ambiguity is present.

b) *Rotational Data*

Although extensive catalogs of stellar rotational velocities have been published (Uesugi and Fukuda 1970; Bernacca and Perinotto 1970, 1971; Bernacca 1973), we have preferred to assign a rotational velocity—when available—to each of our X-ray stellar sources only after completing a new search of all the relevant literature and a critical analysis of the data. We have used the catalogs only for purposes of comparison.

Projected rotational velocities $v \sin i$ (where v is the equatorial velocity and i is the rotation axis inclination angle with respect to the line of sight) have been derived from papers published from 1949 (Slettebak 1949) to 1979. All the papers published during the period 1949–1969 enter into the compilation by Uesugi and Fukuda, who also considered papers published previously, starting from 1929. Bernacca and Perinotto used a selected number of papers published during the period 1949–1969. About one-half of the papers we used (more than 50) were published after 1970.

Since rotational data from different sources were obtained with different dispersions and are of different quality, we have made an effort to estimate their accuracy and to reduce them to the same scale. As a standard, we have adopted the scale established at $v \sin i \gtrsim 20$ km s^{-1} by the classic papers by Slettebak (1949, 1954, 1955, 1956, 1963; Slettebak and Howard 1955). With respect to this scale, the more recent data of Slettebak *et al.* (1975) should be increased by ~5% for A and F stars and ~15% for B stars, while the data by Conti and Ebbets (1977) for O stars must be increased by ~30% at $v \sin i \lesssim 150$ km s^{-1}. Data from Buscombe (1969) can be placed on the same scale by reducing them by ~45% (see also Buscombe and Stoeckley 1975). Similar corrections have been made whenever necessary.

For lower rotational velocities ($v \sin i \lesssim 20$ km s^{-1}) Slettebak's scale is not defined and we have assumed as standard the scale established by Kraft (1965, 1967*a*) on the basis of Hyades and Coma cluster data. With respect to that scale, the more recent, more accurate data[5] by Smith (1976, 1978, 1979), Smith and Dominy (1979), and Gray and Martin (1979), based on Fourier techniques appear to be higher by up to a factor of 2, and a correction must be made to ensure internal consistency.

Rotational data have been determined from line widths given by Huang (1953) by using his interpolation formula and a γ factor of 1.25. Low weight, however, has been attributed to Huang's data, given the uncertainty of the γ value. For dMe stars for which no reliable spectroscopic determination of $v \sin i$ is available, equatorial rotational velocities v_{eq} have been determined from the photometric period, attributed to spot rotation (Kron 1952; Bopp and Fekel 1977).

For all stars for which more than one rotational measurement was available, a weighted average of the different (corrected) values has been computed and adopted as the $v \sin i$ value; a probable error has also been assigned as a measure of the reliability of the adopted value. For stars with narrow lines (with respect to the dispersion of the spectrograph used), only an upper limit on $v \sin i$ has been assigned.

We have found 69 stars[6] for which X-ray luminosities and reliable rotational velocities are available; for ~20% of these stars, however, the $v \sin i$ values are only upper limits. Our data sample contains 33 main-sequence stars, 10 subgiants, 14 giants, and 12 supergiants of all spectral types observed by the *Einstein* survey. In conjunction with the above sample, we have included in the figures the relative locations of the RS CVn stars from Walter and Bowyer (1981). The names of stars used, their spectral types, the values of L_x, L_{bol}, and $v \sin i$, and references are all given in Table 1.

III. RESULTS

a) *Overview*

A plot showing the relationship of X-ray luminosity L_x and projected rotational velocity $v \sin i$ for all stars of our data sample is shown in Figure 1. Different symbols are used to indicate different luminosity classes. Although there is a general tendency of the X-ray luminosity to increase for increasing values of $v \sin i$, the plot appears to be essentially a scatter diagram, especially for rotational velocities $v \sin i \gtrsim 50$ km s^{-1} (i.e., mostly stars of spectral types earlier than ~F). At lower rotational velocities ($v \sin i \lesssim 50$ km s^{-1}, i.e., mostly stars of spectral type later than ~F), the tendency of L_x to increase with $v \sin i$ appears more pronounced if allowance is made for the numerous upper limits on $v \sin i$. Note, however, that there is a sharply defined boundary across which essentially no stars appear. This boundary extends from low luminosity, low rotation, to high luminosity, high rotation. The boundary roughly follows a law of the form $L_x \propto (v \sin i)^3$.

In the following we will examine the relationship between X-ray luminosity and projected equatorial rotational velocity by subdividing the data sample into subgroups of similar spectral type. Figure 1 mixes together stars of all spectral types and luminosity classes; there is no *a priori* reason to assume that a single relation holds throughout the entire H-R diagram. It will be immediately apparent that rotation is *not* an important factor in determining the X-ray emission level of early type stars, and these will be discussed separately. We then examine the individual subclasses more closely to determine whether there exist dependencies on luminosity or rotation in later spectral types and to determine the extent to which the relations are applicable.

We note that several causes may contribute to an observed scatter. First, the quantity $v \sin i$ does not permit an adequate accounting for projection effects in a small data sample. There will thus be a spread along the *X*-axis in our plots due only to the statistical distri-

[5] We have chosen to adjust all measurements to the scale established by the older but more extensive data set. The large lever arm in $v \sin i$ which we have in our data (a factor of >20, see Figs. 5 and 7) and the observed strong dependence of X-ray emission on rotation allow us to formulate conclusions which will not change in a substantive way, even with a factor of 2 change in velocity scale.

[6] After this paper was accepted for publication, we received a preprint from D. Soderblom (Soderblom 1981) containing new rotation measurements for solar-type stars. There are five stars in his list which we had included in the table; for four of these there is no significant difference between our adopted $v \sin i$ and that quoted by Soderblom. In the case of ι Per, an upper limit of 15 km s^{-1} is now given by Soderblom as 3.5 ± 0.7 km s^{-1}; this new determination has been added to Figure 7.

TABLE 1

SUMMARY OF DATA FOR STARS USED IN THIS WORK

(L_x vs. $v \sin i$)

No.	Star	Sp	Adopted[a] $v \sin i$ (km s^{-1})	Notes for[b] $v \sin i$	log L_x	log L_{bol}	Notes[c] for L_x
1	θ^1 Ori C	O7 V	130±10	1, 9, 15, 32, 48	32.2	38.6	(a)
2	θ^2 Ori A	O9.5 V	160±20	1, 9, 15, 32, 48	31.3	38.4	(a)
3	HD 93205	O3 V	165±15	48	33.0	39.6	(a)
4	HD 93250	O3 V	85±15	48	33.3	39.8	(a)
5	μ Col	O9.5 V	115±20	3, 19, 26, 30, 43, 48	32.0	38.3	(b)
6	ζ Oph	O9.5 V	370±30	1, 9, 19, 18, 21, 26 41, 43, 48, 52	31.0	38.5	(b)
7	χ Car	B2 IV	70±20	3, 30, 41	30.0	37.6	(a)
8	α Vir (Spica)	B1 IV	150±20	10, 36, 52	30.3	37.9	(b,c)
9	HD 93403	O5 IIIf	285±25	48	33.0	39.5	(a)
10	τ Ori	B5 III	30±10	3, 7, 41, 42	30.2	37.0	(a)
11	ξ Per	O7.5 III	210±20	1, 9, 48	31.1	38.8	(b)
12	ι Ori	O9 III (+B3p)	120±20	1, 9, 15, 26, 41, 48	32.4	39.0	(b,c)
13	β Cen A	B1 III	105±25	3, 30, 36, 41	30.7	38.1	(b)
14	δ Per	B5 III	240±30	1, 7, 41	29.2	36.6	(b)
15	δ Ori A	O9.5 II	140±10	3, 9, 14, 15, 26 32, 48	32.5	39.2	(a)
16	HD 93129A	O3 If	150±20	48	33.6	40.2	(a)
17	ϵ Ori	B0 Ia	80±10	3, 9, 27	32.3	39.2	(a,l)
18	κ Ori	B0.5 Ie	80±10	3, 9, 27	31.8	39.1	(a,l)
19	ρ Leo	B1 Iab	60±10	3, 9, 42	31.1	38.8	(a,l,q)
20	67 Oph	B5 Ib	25±5	3, 7, 15, 26, 42	31.3	38.1	(a,l)
21	α Cam	O9.5 Ia	90±15	1, 3, 9, 27, 48	32.2	39.4	(l,q)
22	29 CMa	O7 Ia	150±15	9, 48	31.9	39.4	(l,q)
23	ζ Pup	O4 If	200±20	9, 26, 35, 48	32.2	39.5	(b)
24	ζ Ori A	O9.7 Ib	120±20	3, 9, 48	32.4	39.2	(b)
25	α Lup	B2	17±5	3, 30, 36, 41	29.6	37.4	(b)
26	9 Sgr	O5	150±20	1, 9, 48	32.7	39.7	(l,q)
27	β Per (Algol)	B8 V (+K IV+A5)	60±10	3, 4, 28, 34, 59	30.7	35.9	(a,d)
28	α CMa (Sirius)	A1 V	10±5	3, 4, 24, 31, 37, 41 44, 46, 47, 53	26.9	35.0	(a)
29	α Lyr (Vega)	A0 V	15±5	3, 4, 24, 25, 41, 47	27.6	35.4	(a)
30	α^2 CVn	B9.5 V	30±10	3, 4, 12, 15, 29	29.0	35.7	(a,e)
31	γ Gem	A0 IV	<10	3, 4, 23, 24, 25 39, 41	29.2	35.8	(a,r)
32	δ Cyg	B9.5 III	130±10	3, 4, 25, 41	29.1	35.8	(a)
33	α Oph	A5 III	210±30	3, 5, 8, 25, 41	28.6	35.2	(a)
34	ϵ Sgr	B9 IV	175±45	37	29.8	36.4	(b)
35	α^1 CVn	F0 V	≤20	3, 6, 12, 15	29.0	34.5	(a,e)
36	HR 4574	A9 V	80±10	38	29.0	34.5	(a)
37	α Car (Canopus)	F0 Ib	≤15	3	30.0	37.3	(a)
38	α Hyi	F0 V (or A9 III)	145±20	3, 41	27.9	34.7	(a)
39	ρ Psc	F2 V	60±10	3, 20	29.2	34.2	(a)
40	46 Tau	F3 V	60±5	3, 6, 8	29.1	34.5	(a)
41	HR 1436	F5 V	35±10	17	28.9	34.2	(a)
42	ν^2 Col	F4 V	35±10	3	28.7	34.0	(a)
43	HD 108102	F7 V	35±10	17	29.9	34.0	(a)
44	θ Cyg	F4 V	7±2	3, 6, 8, 20, 22, 38	28.7	34.0	(v)
45	β Vir	F8 V	3±1	3, 6, 8, 16, 20, 22 41, 54	28.4	34.0	(a,m)
46	HD 8774	F7 IV	20±5	38	29.2	34.5	(a)
47	α Tri	F6 IV	90±15	3, 5, 6, 8, 41	29.5	34.7	(a)
48	ι Per	G4 V	<15	6, 8, 16, 20	27.6	34.0	(a)
49	π^1 UMa	G0 V	8±3	16, 20, 22, 54	29.1	33.6	(a)
50	α Cen A	G2 V	3±1	40, 54, 58	27.1	33.6	(a)
51	β Com	G0 V	4.5±1.5	5, 6, 8, 16, 20 22, 54	28.3	33.6	(a,m)

TABLE 1 —*Continued*

No.	Star	Sp	Adopted[a] $v \sin i$ (km s^{-1})	Notes for[b] $v \sin i$	log L_x	log L_{bol}	Notes[c] for L_x
52	ε Eri	K2 V	<15	6	28.3	33.1	(a,n,p)
53	EQ Vir	K5 V	10±2	49,50	29.4	32.3	(a)
54	70 Oph A	K0 V	2±1	6,15,54	28.1	33.2	(a,n,p,f)
55	70 Oph B	K5 V	≤25	15	28.1	32.5	(a,n,p,f)
56	61 Cyg A	K5 V	2±1	6,15,57	27.2	32.5	(a,n,p,f)
57	61 Cyg B	K7 V	≤25	15	27.2	32.1	(a,n,p,f)
58	YY Gem	M1 Ve	40±5	2,11,49	29.6	32.2	(a,g)
59	YZ CMi	M4.5 Ve	5±1	33,49	28.5	30.6	(v,h)
60	24 UMa	G2 IV	<25	6,8	30.0	34.5	(a,o,s)
61	η Boo	G0 IV	<15	3,5,6,8,16,20	28.0	34.4	(a)
62	μ Her A	G5 IV+ (2 M stars)	<15	6,8	27.6	34.0	(a,i)
63	α Aur (Capella)	G5 III+ G0 III	30±10 (sec.)	6,60	30.3	35.8	(a,j)
64	β Lep	G5 III	11±2	5,6	29.2	36.1	(a)
65	η Dra	G8 III	<15	6	27.9	35.2	(a)
66	β Gem	K0 III	2±1	6,55,56	27.8	35.2	(t)
67	α Ser	K2 III	2±1	6,55,56	27.8	35.2	(a)
68	ζ And	K1 II-III	35±5	5,6,45,51	29.9	34.6	(u)
69	Z Her	K0 IV	33±5	45,51	30.3	34.0	(a,k)

[a]For an explanation of the relative weights given to various sources and the velocity scales adopted, see text (§ II b).

[b]Notes for $v \sin i$.—(1) Slettebak 1949. (2) Kron 1952. (3) Huang 1953. (4) Slettebak 1954. (5) Oke and Greenstein 1954. (6) Herbig and Spalding 1955. (7) Slettebak and Howard 1955. (8) Slettebak 1955. (9) Slettebak 1956. (10) Struve *et al.* 1958. (11) Struve and Zebergs 1959. (12) Slettebak *et al.* 1961. (13) Meadows 1961. (14) Abt and Hunter 1962. (15) Slettebak 1963). (16) Wilson and Skumanich 1964. (17) Kraft 1965. (18) Koch *et al.* 1965 (19) Wallerstein and Wolff 1965. (20) Wilson 1966. (21) Slettebak 1966. (22) Kraft 1967*a*. (23) Kraft 1967*b*. (24) Deutsch 1967. (25) Palmer *et al.* 1968. (26) Buscombe 1969. (27) Rosendhal 1970. (28) van den Heuvel 1970. (29) Preston 1970. (30) Levato and Malaroda 1970. (31) Geary and Abt 1970. (32) Abt *et al.* 1970. (33) Gershberg 1970. (34) Hill *et al.* 1971. (35) Baschek and Scholtz 1971. (36) Watson 1972. (37) Levato 1972. (38) Danziger and Faber 1972. (39) Dworestsky 1974. (40) Boesgaard and Hagen 1974. (41) Slettebak *et al.* 1975. (42) Day and Warner 1975. (43) Buscombe and Stoeckley 1975. (44) Smith 1976. (45) Hall 1976. (46) Deeming 1977. (47) Milliard *et al.* 1977. (48) Conti and Ebbets 1977. (49) Bopp and Fekel 1977. (50) Anderson *et al.* 1977. (51) Popper and Ulrich 1977. (52) Hutchings and Stoeckley 1977. (53) Kurucz *et al.* 1977. (54) Smith 1978. (55) Gray and Martin 1979. (56) Smith and Dominy 1979. (57) Vogt and Fekel 1979. (58) Smith 1979. (59) Rucinsky 1979. (60) Ayres and Linsky 1980.

[c]Notes for L_x: (*a*) Vaiana *et al.* 1981. (*b*) Long and White 1980. (*c*) For the primary star. (*d*) Rotation rate of primary, but X-ray emission likely to originate from the K-component. (*e*) L_x refers to the total emission from α^1 and α^2 CVn. (*f*) Total X-ray luminosity split equally between the A and B components. (*g*) v_{eq} derived from setting eclipse period equal to photometric period. (*h*) v_{eq} derived from photometric period. (*i*) L_x refers to the total flux from the system, G5 IV+M stars. (*j*) X-ray emission attributed to the secondary. (*k*) v_{eq} derived from the orbital period assuming synchronous rotation. (*l*) Program of Guest Observer J. Cassinelli. (*m*) Program of Guest Observer J. L. Linsky. (*n*) Program of Guest Observer H. M. Johnson. (*o*) Program of Guest Observer K. Zwaan. (*p*) Johnson 1981. (*q*) Cassinelli *et al.* 1981. (*r*) Program of Guest Observer A. Fabian. (*s*) Mewe and Zwann 1981. (*t*) Ayres *et al.* 1981. (*u*) Walter *et al.* 1980. (*v*) CfA unpublished.

bution in stellar orientations. Second, there may be X-ray variability in late type stars, resulting in a broadening of the distribution parallel to the Y-axis. The solar X-ray luminosity varies by slightly more than one order of magnitude in the IPC X-ray passband during a solar cycle (Kreplin 1970; Kreplin *et al.* 1977), with flaring activity contributing another factor of 2 for short periods.

b) *Early Type Stars (O–B)*

Figure 2 shows a plot of L_x versus $v \sin i$ for early type stars of spectral type O3 to B5 (and spectral types B8–A5, to be discussed later). Different symbols indicate different luminosity classes. We do not find any obvious correlation between X-ray luminosity and equatorial rotational velocity, either for the entire sample of early type stars or within each luminosity class. This is especially true for main-sequence stars and giants (which may have X-ray luminosities different by more than three orders of magnitude for stars of comparable rotational velocities). Only supergiants, taken alone, show some tendency of the X-ray luminosity to increase with increasing rotational velocities; we believe, however, that this is a selection effect and is simply due to the combined effects of the dependence of L_x on bolometric luminosity (see later in this section) and of the *statistical* dependence of rotational velocities on effective temperature for early type supergiants (see, e.g., Rosendhal 1970).

The apparent absence of any clear correlation between L_x and $v \sin i$ for early type stars is contrasted by a strong dependence of L_x on bolometric luminosity L_{bol}. This is shown in Figure 3, where L_x is plotted as a

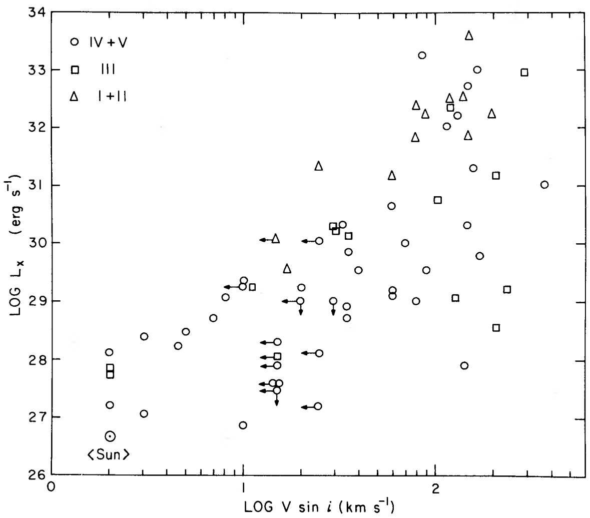

FIG. 1

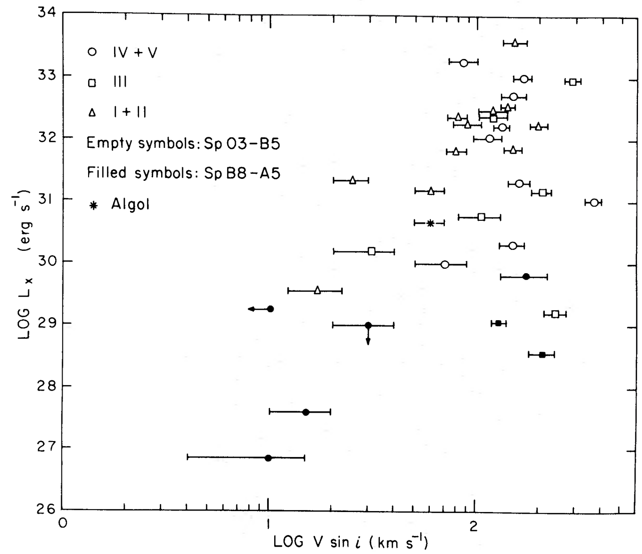

FIG. 2

FIG. 1.—Scatter diagram of X-ray luminosities vs. projected rotational velocities for stars of various spectral types and luminosity classes detected by the *Einstein* Observatory. Different symbols indicate different luminosity classes. The X-ray luminosities are from published surveys by Vaiana *et al.* (1981) and Long and White (1980), and other sources as indicated in the notes to Table 1. The rotational data are from a variety of published sources; values used in the plot are weighted averages of the available measurements, all reduced to the Slettebak-Kraft scale. Notice that at low rotation rates, only upper limits of $v \sin i$ are available for many stars.

FIG. 2.—Scatter diagram of X-ray luminosities vs. projected rotational velocities $v \sin i$ for stars of spectral types O3<b5 (*empty symbols*) and of spectral types B8–A5 (*filled symbols*). Different symbols indicate different luminosity classes. The horizontal bars indicate the probable errors on the adopted values of $v \sin i$. Notice that there is no obvious correlation between X-ray luminosites and rotational velocities for both groups of stars O3–B5 and B8–A5 separately. The peculiar system Algol may not belong to the same subset of stars, since X-ray emission is likely to originate from the K0 IV component, rather than from the B8 V primary.

function of L_{bol} for the same stars used in Figure 2 (plus additional B8–A5 stars to be discussed later). L_x appears well correlated with L_{bol}, and a best fit relationship gives approximately $L_x \approx 10^{-7} L_{bol}$ with a scatter of the order of a factor of 3 about the best fit line.[7] There is no indication of systematic differences between different luminosity classes. A similar dependence of X-ray luminosity on bolometric luminosity for early type (O and B) stars had previously been suggested by a number of authors on the basis of sparser data (Harnden *et al.* 1979; Long and White 1980; Cassinelli *et al.* 1981).

The conclusions above may be somewhat affected by the well-known uncertainties on the determination of rotational velocities of early type stars (especially O stars), owing to the difficulties of separating macroturbulence and rotation from the observed broadened line profiles (Slettebak 1956; Rosendhal 1970). Macroturbulence is thought to become increasingly important with respect to rotation at higher effective temperatures and luminosities (Ebbets 1979). If line broadening in O and early B stars is a measure of macroturbulence rather than rotation, and if macroturbulence increases—as appears to occur—for increasing stellar masses, it is not surprising to find an apparent correlation of L_x and line broadening for early type supergiants, given the relationship which exists between L_x and mass.

On the basis of Figures 2 and 3 we conclude that the X-ray luminosity of early type stars is largely independent of rotational velocity, and is mainly determined by bolometric luminosity, being simply proportional to it to a good approximation . We note that a lack of correlation between X-ray level and mass loss rates for these stars has been pointed out by Vaiana (1980*c*).

c) A Stars

We have considered together stars of spectral types B8 to A5, and we have correlated their X-ray luminosity with both equatorial rotational velocity and bolometric luminosity. As reported by Vaiana *et al.* (1981), stars around spectral type A0 show a very broad range of X-ray emission levels, from $\sim 10^{27}$ ergs s^{-1} for stars such as Sirius and Vega to $\sim 5 \times 10^{30}$ ergs s^{-1} in the multiple system Algol.

[7]The average ratio L_x/L_{bol} for O3–B5 stars is $(1.4 \pm 0.3) \times 10^{-7}$; the quoted errors are 1 s.d., based on the dispersion in the data.

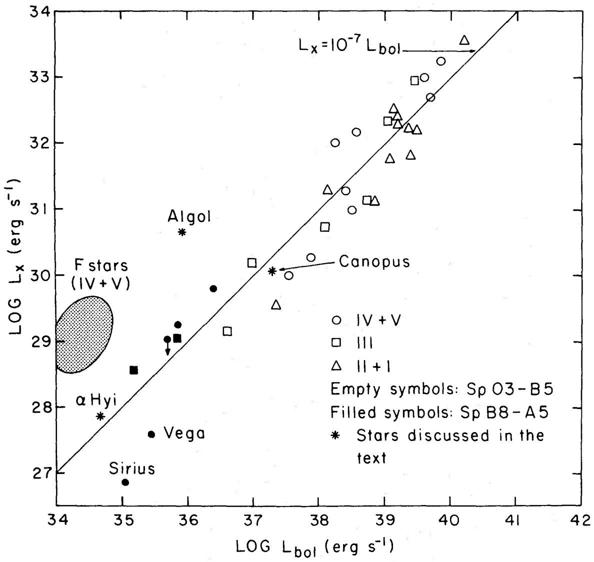

FIG. 3.—X-ray luminosity versus bolometric luminosity for stars of spectral types O3–B5 (*empty symbols*) and of spectral types B8–A5 (*filled symbols*). Different symbols indicate different luminosity classes. The stars plotted are the same as in Fig. 2 except for Canopus (F0 Iab) and α Hyi (F0 V or A9 III). The position of main-sequence and subgiant stars of spectral type F is also indicated schematically. Notice the good correlation between X-ray luminosity and bolometric luminosity for the entire group of stars of spectral type O3–A5 as well as for the two subgroups O3–B5 and B7–A5, separately. The straight line corresponds to the relationship $L_x = 10^{-7} L_{\rm bol}$.

We have found no clear correlation between X-ray luminosity and rotational velocity for our small sample of A stars (see Fig. 2); on the contrary, we find some evidence of a possible extension to A stars of the relationship $L_x \sim 10^{-7} L_{\rm bol}$ valid for earlier spectral types. This is shown in Figure 3, where data points for B8–A5 stars (identified with filled symbols) have been plotted together with O3–B5 stars.

Although our sample of ~A stars is rather limited (only seven stars of spectral type B8–A5), we find that most of the data points are aligned along the average relationship found for earlier spectral types. The only notable exception is represented by the peculiar system β Per (Algol); this can be easily explained, however, if the dominant source in the system is the K star (White *et al.* 1980). The X-ray emission of Sirius and Vega is somewhat lower than expected but may still be consistent with the same relationship, if the spectrum of these stars is very soft (see Golub *et al.* 1981) and the X-ray luminosity is somewhat underestimated. If the extension to A stars of the relationship $L_x \sim 10^{-7} L_{\rm bol}$ is correct, one would typically expect for main-sequence stars and giants of spectral type A, X-ray luminosities in the range $\sim 10^{27}-10^{28}$ ergs s^{-1}. There is some evidence (Golub *et al.* 1981) that A stars with higher X-ray luminosity levels are unresolved binary systems with a late type companion whose emission is dominant at X-ray wavelengths, whereas the nearest A stars, such as Sirius, Vega, and Altair, are found to emit at $\sim 10^{27}-10^{28}$ ergs s^{-1}.

At spectral types later than ~A5 the relationship between X-ray luminosity and bolometric luminosity no longer holds. For instance, F stars (indicated schematically in Fig. 3) are one to two orders of magnitude more luminous in X-rays than expected on the basis of the X-ray versus bolometric luminosity relation.

It is worth noticing that *evolved* stars of spectral type F0 still appear to follow the dependence of X-ray luminosity on bolometric luminosity. This occurs for the supergiant star α Car (F0 Iab) which has $L_x/L_{\rm bol} = 5 \times 10^{-8}$. The same occurs for α Hyi (which has $L_x/L_{\rm bol} \sim 1.5 \times 10^{-7}$), a fact which supports the view that this is an A9 III star (as reported by de Vaucouleurs 1957), rather than an F0 V star as is usually given (Hoffleit 1964). The X-ray luminosity of α Hyi is a factor ~25 lower than the median X-ray luminosity of F stars (Vaiana *et al.* 1981), while its rotational velocity ($v \sin i = 145$ km s^{-1}) is the highest among F stars in our data sample. Rotation, therefore, does not seem to be very important in determining the level of X-ray emission of α Hyi.

d) *F Stars*

In Figure 4 we plot L_x versus $v \sin i$ for F stars (our data sample contains only main-sequence and subgiant stars of spectral type A9–F8; the supergiant α Car and the possible giant α Hyi are treated separately for the reasons mentioned above). While F stars show a rather narrow range of X-ray luminosity levels (at $\sim 10^{29}$ ergs s^{-1}, Vaiana *et al.* 1981), their spread in rotational velocity is much larger (from less than ~10 km s^{-1} to ~100 km s^{-1}). The latter is in agreement with the well-known steepness of the average rotational velocity curve around spectral type F (Slettebak 1970; Kraft 1970).

As a consequence of the very different ranges of L_x and $v \sin i$ values, we find only a weak dependence [$L_x \sim (v \sin i)^{0.5}$] of X-ray luminosity on rotational velocity for F stars. We note, however, that the X-ray luminosity of F stars is substantially higher than would be expected on the basis of the bolometric luminosity relation which was found in early type stars (Fig. 3); and that as a class, F stars have both higher X-ray luminosities and higher average rotational velocities than G and later type stars. These two facts taken together suggest that (1) the X-ray luminosity of F stars is determined by an additional parameter other than bolometric radiative flux; (2) rotation, even if apparently not very important within the class itself, may be somewhat responsible for the higher X-ray luminosity of F stars as a whole with respect to G and later spectral type main-sequence stars (whose coronal emission is found to be strongly correlated with rotation, see later).

It seems reasonable to assume that the increased X-ray luminosity of F stars with respect to single A stars is primarily due to the combined effects of the onset of convection and the rapid change in rotation at F, which may be strong enough to mask the kind of dependence of X-ray emission on rotation observed for the remaining late type stars. We should note, however, that an extrapolation to F stars of the relationship $L_x \sim (v \sin i)^2$ found for later spectral types gives for an average rotational velocity of ~ 40 km s^{-1} a somewhat higher X-ray luminosity than observed in F stars; the relevance of rotation for F stars remains therefore somewhat conjectural at the present stage.

e) *Late Type Stars* (*G–M*)

It is well known (see, e.g., Slettebak 1970; Kraft 1970) that stars of spectral type G and later are generally very slow rotators, with rotational velocities undetectable at moderate dispersion ($v \sin i \lesssim 20$ km s^{-1}). This is unfortunate, since late type stars (which possess subphotospheric convection zones, and hence have the possibility of sustaining magnetic field generating dynamo mechanisms) may be expected to be the most appropriate to show any dependence of X-ray luminosity on rotation rate.

In order to investigate the relation between rotation and coronal emission, we have relied principally on (1) recent measurements of rotational rates via Fourier techniques (capable of attaining a maximum sensitivity of ~ 2 km s^{-1}; see review by Smith 1979); (2) rotational rates of M stars based on photometric periodicity, attributed to the presence of starspots (Bopp and Fekel 1977; Anderson, Schiffer, and Bopp 1977). Although this is the best we can do at the present time, we emphasize that the data are still rather scarce and that new high-sensitivity determinations of rotational velocities for G and later type stars would be highly desirable.

Using the data at our disposal, we have found a good correlation of X-ray luminosity and rotational velocity for the entire group of stars from spectral type $\sim$F7 to M5 and of all luminosity classes so far detected at X-ray wavelengths (V–IV–III). This is shown in Figure 5, where we plot L_x as a function of $v \sin i$; upper limits have been excluded for the purpose of clarity. The position of the RS CVn stars studied by Walter *et al.* (1980) and Walter and Bowyer (1981) has been also schematically indicated. The available data are

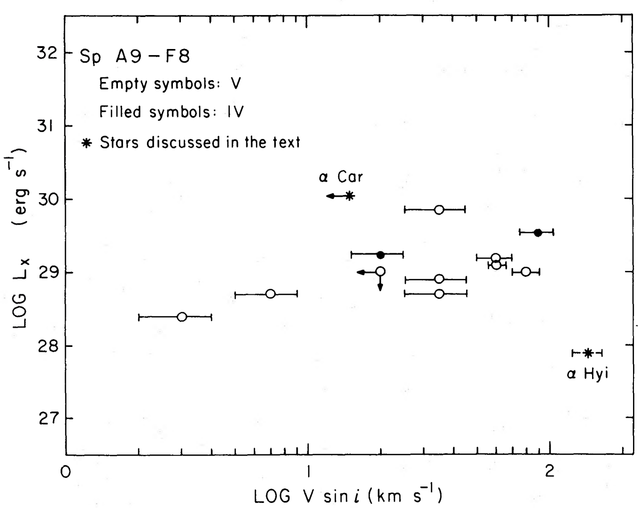

FIG. 4

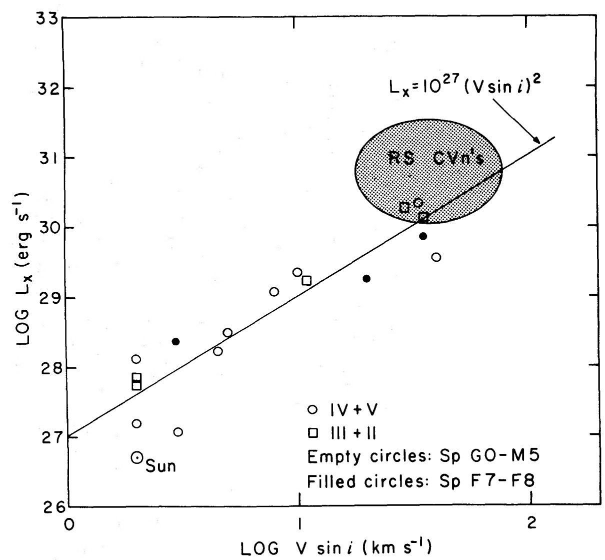

FIG. 5

FIG. 4.—Scatter diagram of X-ray luminosities versus projected rotational velocities for main-sequence stars (*empty circles*) and subgiants (*filled circles*) of spectral type F (from A9 to F8). The data points corresponding to the supergiant star Canopus (α Car, F0 Iab) and the possible giant α Hyi (F0 V or A9 III) are also indicated. The data plotted are a subset of the same stars shown in Fig. 1. The horizontal bars indicate the probable errors on the adopted values of $v \sin i$. Notice that F stars show only a weak dependence on rotation within the class itself.

FIG. 5.—Scatter diagram of X-ray luminosities versus projected rotational velocities for stars of spectral type G0–M5 (*empty symbols*) and of late type F (F7–F8) (*filled symbols*). Different symbols indicate different luminosity classes. The data points are a subset of the stars shown in Fig. 1. The position of RS CVn stars (both short and long period systems) is indicated (from Walter *et al.* 1980); the plotted X-ray luminosity of the Sun is an average over the solar cycle. Notice that the entire sample of stars from F7 to M5 shows a correlation of the X-ray luminosity with rotation rate: the straight line corresponds to the relationship $L_x = 10^{27} (v \sin i)^2$ with $v \sin i$ expressed in km s^{-1}. Stars for which only upper limits for $v \sin i$ are available have not been plotted, but they are consistent with the same relationship (see also Figs. 7*a*, *b*, *c*).

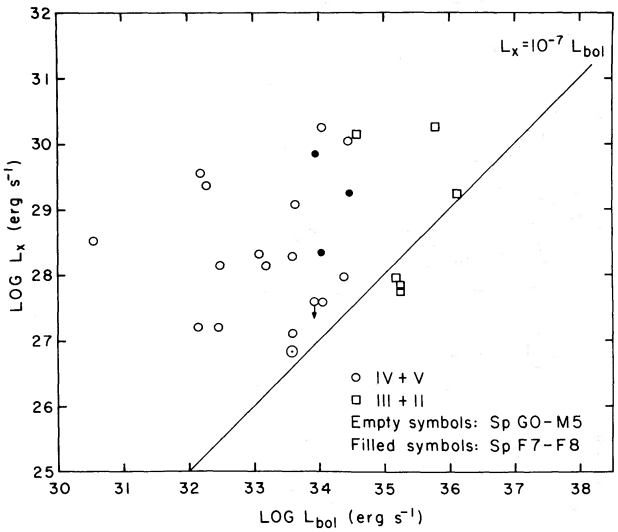

FIG. 6.—Scatter diagram of X-ray luminosities versus bolometric luminosities for stars of spectral type G0–M5 (*empty symbols*) and of late type F (F7–F8) (*filled symbols*). The stars plotted are the same as in Fig. 5. Different symbols indicate different luminosity classes. The straight line corresponds to the relationship $L_x = 10^{-7} L_{bol}$ found to hold for early spectral types (O3–A5; see Fig. 3). Notice that stars of spectral type F7 to M5 appear to have X-ray luminosities uncorrelated with bolometric luminosities.

consistent with a relationship[8] L_x (ergs s^{-1}) ~ 10^{27} ($v \sin i$[km s^{-1}])^2. The same stars do not show any dependence of X-ray luminosity on bolometric luminosity (Fig. 6).

The same trend of L_x increasing with increasing values of $v \sin i$ appears to be present within each spectral type (see Figs. 7*a*, *b*, *c*), although the exact functional dependence may differ from one spectral type to another. The paucity of data, however, as well as uncertainties of rotational velocities and possible temporal variations of the X-ray flux, render the dependence on spectral type uncertain, and we must defer this point to future investigation.

There is no indication that stars of the same spectral type but different luminosity classes have different dependences on rotational velocity: on the contrary, *main-sequence stars and giants of spectral types G and K* (see Figs. 7*a*, *b*) *appear to follow the same relationship between L_x and $v \sin i$*. This remarkable observational fact would be lost if the data were replotted in a different manner, e.g., by plotting L_x versus angular velocity Ω, which would introduce an artificial spread among stars of the same temperature but different radius. Notice that the multiple system β Per (Algol) fits nicely with the rotational dependence found if the system is in synchronous rotation and the radius of the K0 subgiant

[8]A least-squares fit gives $L_x \sim 1.4 \times 10^{27}$ $(v \sin i)^{(1.9 \pm 0.5)}$. If we set the exponent equal to 2, this relation may be conveniently rewritten $f_x \approx 1.1 \times 10^{16}$ Ω^2_{proj}, thus relating the average X-ray surface flux and the angular velocity projected against the sky.

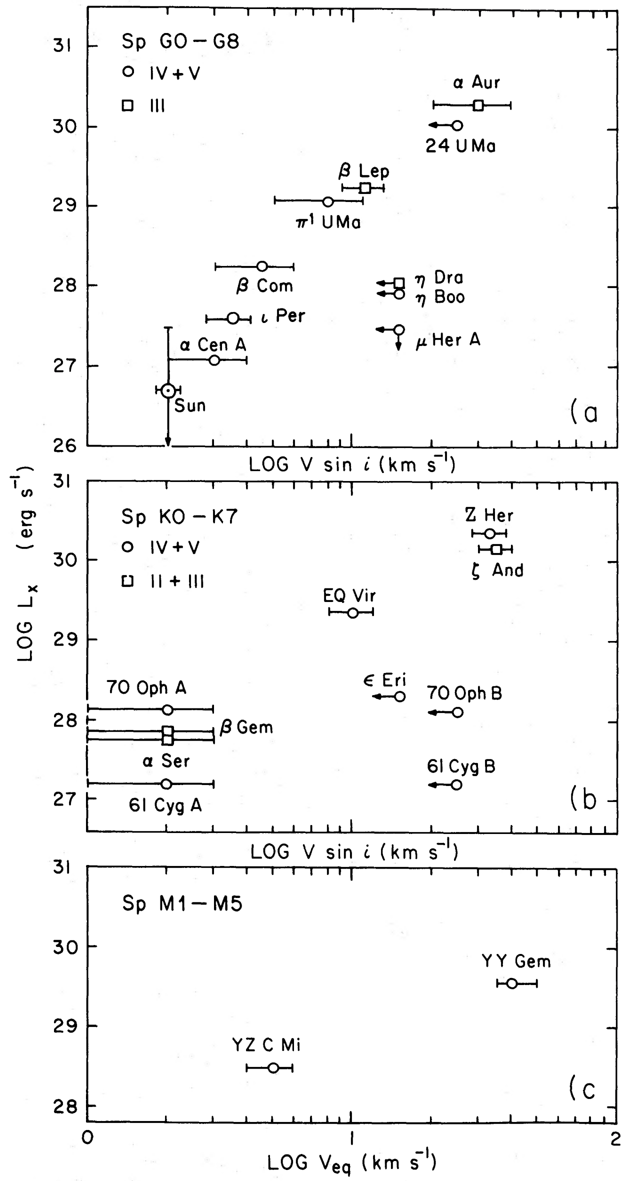

FIG. 7.—Scatter diagram of X-ray luminosities versus projected rotational velocities $v \sin i$ (or equatorial rotational velocities v_{eq} for M stars) for stars of spectral types: (*a*) G0 to G8, (*b*) K0 to K7, (*c*) M0 to M5. Different symbols indicate different luminosity classes. The horizontal bars indicate the probable errors on the adopted values of $v \sin i$. The stars plotted are a subset of the data points shown in Fig. 1. The point for the Sun shows the range of variation of X-ray luminosity during the solar cycle. Notice that within each spectral type G to M, the X-ray luminosity shows a tendency to increase for increasing values of rotation rate. Upper limits of $v \sin i$ are consistent with the same trend.

is approximately equal to that of the B8 V primary. This supports the idea that the dominant component in the system is the K0 IV star.

As shown schematically in Figure 5, the average of the data on RS CVn stars (from Walter *et al.* 1980) appears to be consistent with the same relationship

$L_x \sim (v \sin i)^2$ shown by late type stars. That is, the centroid of the RS CVn data falls on the continuation of the L_x versus $v \sin i$ line obtained from the other late type stars. This would support the view that RS CVn variables are not physically different from other late type stellar X-ray sources and that their enhanced chromospheric and coronal emission is due to enforced rapid rotation of the late type component.

We note, however, that while as a class RS CVn systems appear to be consistent with the general dependence of X-ray luminosity on rotation, there is very little, if any, observed dependence within the RS CVn sample of X-ray luminosity on $v \sin i$; the L_x versus $v \sin i$ plot is consistent with a low-power dependence. This is independently true for *both short- and long-period RS CVn systems*, which further *do not show any significant difference in their X-ray luminosity functions* (Walter and Bowyer 1981). Thus, RS CVn stars differ markedly in their detailed behavior from other late type stars, for which the V^2 dependence of L_x is easily discernible.

Our result does not necessarily contradict the dependence of L_x on rotation found by Walter and Bowyer (1981) $[L_x/L_{\rm bol} \sim \Omega]$. We note that the long-period systems are generally giants, but in short-period systems the dominant emitters are usually subgiants. Since the total X-ray emission levels are about the same in the two groups, and since the average $T_{\rm eff}$ is the same, the use of the parameter $L_x/L_{\rm bol}$ introduces an extra R^{-2} dependence. Since $\Omega \sim V/R$, the finding that L_x versus $v \sin i$ is nearly flat is completely consistent with the relation $L_x/L_{\rm bol} \sim \Omega$. Given the present status of dynamo theory and theories of coronal formation, there are no reliable theoretical scaling laws by which X-ray emission can be directly related to rotation or to depth of convective zones, although plausibility arguments do exist. At the moment, there appear to be no *a priori* grounds for deciding whether a relation between L_x and V, or between $L_x/L_{\rm bol}$ and Ω, is more fundamental. In fact, the present study indicates that neither is applicable to all stars, or even to all late type stars, although we are clarifying the limits of applicability of these scaling relations.

IV. DISCUSSION AND CONCLUSIONS

We have correlated X-ray luminosity and equatorial rotational velocity $v \sin i$ for stars of different spectral types and luminosity classes. The main conclusions of this paper can be summarized as follows:

1. *Early type stars* (O–B) have X-ray luminosities largely independent of rotational velocities; instead, X-ray emission correlates with the bolometric luminosities. To first approximation, we find $L_x \approx 10^{-7} L_{\rm bol}$ with little scatter about the mean. The above relationship does not appear to depend on luminosity class.

2. There are indications that the same dependence of X-ray luminosity on bolometric luminosity may extend down to spectral type ~A5 for main-sequence stars and perhaps to spectral type ~F0 for evolved stars. Stars of spectral type A do not appear to show any clear correlation between X-ray luminosity and rotational velocity.

3. *Late type stars* of spectral type G to M have X-ray luminosities well correlated with equatorial rotational velocities. We find a relationship $L_x(\text{ergs s}^{-1}) \sim 10^{27} (v \sin i[\text{km s}^{-1}])^2$ for the ensemble of all late type (F7 to M5) stars of *all luminosity classes*. A dependence of X-ray luminosity on equatorial rotational velocity appears to hold for each spectral type separately. Late type stars do not show any correlation between X-ray luminosity and bolometric luminosity.

4. RS CVn stars *as a class* are consistent with the same relationship L_x and $v \sin i$ found for other late type stars. However, within the sample of RS CVn stars presented by Walter and Bowyer (1981), *there is only weak, if any, dependence of X-ray luminosity on rotation rate.*

5. F stars show only a very weak correlation between X-ray luminosity and equatorial rotational velocity. As a class, their behavior appears to be intermediate between early and late type stars. Their median X-ray luminosity is *substantially higher* than expected from their median bolometric luminosity on the basis of the relationship $L_x \approx 10^{-7} L_{\rm bol}$. Both their median X-ray luminosity and average rotational velocity are higher than for spectral types G and later; however, their median X-ray luminosity is somewhat lower than expected from their average rotational velocity on the basis of the relationship L_x (ergs s^{-1})$\sim 10^{27} (v \sin i[\text{km s}^{-1}])^2$.

These results have important implications for theories of coronal formation. They show that, whatever the mechanism of coronal heating may be, the relative importance of different ingredients (radiation, convection, rotation) must differ for stars of different spectral type.

The results reported above are consistent with the scenario of coronal formation suggested by Vaiana (1980*a*, *b*), Rosner and Vaiana (1980), and Linsky (1980). They have proposed the new view that X-ray emission from stellar coronae derives dominantly—as for the Sun—from plasma structures confined by stellar magnetic fields and that the mechanism of coronal heating is likely to be magnetic, rather than acoustic, in nature. In the framework of that model, the good correlation found for late type stars between X-ray luminosity and rotation rate is strong support for the notion that dynamo-generated magnetic fields are responsible for coronal heating in stars possessing subphotospheric convection zones. The local peak of X-ray emission at F stars (Vaiana *et al.* 1981) indicates that convection is an essential ingredient of coronal formation, but it does not appear to be sufficient *per se* (as in the acoustic theory) to explain the existence of a corona. Rather, interaction of rotation and convection leading to magnetic fields and the stressing—and subsequent dissipation—of these fields by surface turbulence driven by convection, appear to be a much more likely explanation for the corona in late type stars.

The first order relationship $L_x \sim (v \sin i)^2$ found for late type stars, together with the small range of masses for the same stars, is suggestive of a dependence of X-ray luminosity on rotational energy[9] $K \sim Mv^2$. Although this may look appealing, care should be executed in interpreting this result. The rotational energy of a normal star is generally a very small quantity when compared with the thermal and gravitational energy, and it is unlikely that the energy ultimately emitted at X-ray wavelengths by a stellar corona originates by direct conversion of rotational energy. For instance, the Sun has a rotational energy $K \approx 3 \times 10^{42}$ ergs (Kraft 1970) and an average X-ray luminosity $L_x \sim 10^{27}$ ergs s^{-1} (Vaiana and Rosner 1978). The typical lifetime for conversion of rotational energy into coronal emission is then only $K/L_x \sim 10^8$ yr, much shorter than the evolutionary time scale. The same result applies to all late type stars, given the approximate proportionality between X-ray luminosity and rotational energy.

Since it is unlikely on observational grounds (Vaiana *et al.* 1981) that X-ray emission from late type stellar coronae is only a transient phenomenon in a star's lifetime, we must conclude that the heating of late type stellar coronae does not result from direct conversion of rotational energy. More likely, rotation is important in maintaining dynamo-generated magnetic fields, with the energy eventually dissipated by magnetic fields coming from thermal and turbulent motions. In this respect, the experimentally determined relationship $L_x \sim (v \sin i)^2$, or equivalently the relationship between X-ray surface flux $f_x = L_x / 4\pi R^2$ and the square of the stellar angular velocity Ω, may be of significant relevance for the still poorly understood mechanism of magnetic field generation via dynamo action.

We would like to thank Charles Maxson for help with the data reduction and preparation of this manuscript. This work has been supported at the CfA in part by NASA under grants NAGW-112 and NAG-8302, by the Langley Abbot Program of the Smithsonian Institution, and by the CNR of Italy. J.L.L. and T.A. also wish to acknowledge support by NASA through grants to the University of Colorado.

[9]For a spherically symmetric star rotating rigidly with angular velocity Ω, the rotational energy is given by:

$$K = \frac{4\pi}{3} \Omega^2 \int_0^R \rho(r) r^4 \, dr,$$

where R is the star radius and $\rho(r)$ is the density distribution within the star. Rotational energies computed with the above formula are generally very different from the rotational energy $\frac{1}{5} Mv^2$ of a constant density sphere. However, computations based on stellar interior models (Schwarzschild 1958) for stars of 0.6, 1, 2.5 and 10 $M_\odot$ show that the *relative* values $(M/M_\odot)\,(v/v_\odot)^2$ with respect to the Sun do not differ from the exact ratios of rotational energies by more than a factor of 2.

REFERENCES

Abt, H. A., and Hunter, J. H., Jr. 1962, *Ap. J.*, **136** 381.
Abt, H. A., Muncaster, G. W., and Thompson, L. A. 1970, *A.J.*, **75**, 1095.
Anderson, C. M., Schiffer, F. H., III, and Bopp, B. W. 1977, *Ap. J.*, **216**, 42.
Ayres, T. R., and Linsky, J. L. 1980, *Ap. J.*, **235**, 76.
Ayres, T. R., Linsky, J. L., Vaiana, G. S., Golub, L., and Rosner, R. 1981, *Ap. J*, submitted.
Baschek, B., and Scholtz, M. 1971, *Astr. Ap.*, **15**, 285.
Bernacca, P. L. 1973, *Contrib. Oss. Astr. Univ. Padova Asiago*, No. 294.
Bernacca, P. L., and Perinotto, M. 1970, *Contrib. Oss. Astr. Univ. Padova Asiago*, No. 239.
______. 1971, *Contrib. Oss. Astrof. Univ. Padova Asiago*, No. 250.
Boesgaard, A. M., and Hagen, W. 1974, *Ap. J.*, **189**, 85.
Bopp, B. W., and Espenak, F. 1977, *A.J.*, **82**, 916.
Bopp, B. W., and Fekel, F., Jr. 1977, *A.J.*, **82**, 490.
Buscombe, W. 1969, *M.N.R.A.S.*, **144**, 1.
Buscombe, W., and Stoeckley, T. R. 1975, *Ap. Space Sci.*, **37**, 197.
Cassinelli, J. P. 1979, *Ann. Rev. Astr. Ap.*, **17**, 275.
Cassinelli, J. P., Waldron, W. L., Sanders, W. T. Harnden, F. R., Rosner, R., and Vaiana, G. S. 1981, *Ap. J.*, submitted.
Conti, P. S. 1978, *Ann. Rev. Astr. Ap.*, **16**, 371.
Conti, P. S., and Ebbets, D. 1977, *Ap. J.*, **213**, 438.
Danziger, I. J., and Faber, S. M. 1972, *Astr. Ap.*, **18**, 428.
Day, R. W., and Warner, B., 1975, *M.N.R.A.S.*, **173**, 419.
de Loore, C. 1970, *Ap. Space Sci.*, **6**, 60.
Deeming, T. J. 1977, *Ap. Space Sci.*, **46**, 13.
Deutsch, A. J. 1967, in *The Magnetic and Related Stars*, ed. R. C. Cameron (Baltimore: Mono), p. 181.
de Vaucouleurs, A. 1957, *M.N.R.A.S.*, **117**, 449.
Dworetsky, M. M. 1974, *Ap. J. Suppl.*, **28**, 101.
Ebbets, D. 1979, *Ap. J.*, **227**, 510.
Geary, J. C., and Abt, H. A. 1970, *A.J.*, **75**, 718.
Gershberg, R. E. 1970, in *Stellar Rotation*, ed. A. Slettebak (New York: Gordon & Breach), p. 249.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Golub, L., Harnden, F. R. Jr., Vaiana, G. S., Snow, T. P., and Cash, W. C. 1981, in preparation.
Gorenstein, P., and Tucker, W. H. 1976, *Ann. Rev. Astr. Ap.*, **14**, 373.
Gray, D. F., and Martin, B. E. 1979, *Ap. J.*, **231**, 139.
Hall, D. S. 1976, in *Multiple Periodic Variable Stars*, ed. W. S. Fitch (Dordrecht: Reidel), p. 287.
Harnden, F. R., Jr., *et al.* 1979, *Ap. J. (Letters)*, **234**, L51.
Herbig, G. H., and Spalding, J. F., Jr. 1955, *Ap.J.*, **121**, 118.
Hill, G., Barnes, J. V., Hutchings, J. B., and Pearce, J. A. 1971, *Ap. J.*, **168**, 443.
Hoffleit, D. 1964, *Catalogue of Bright Stars* (New Haven: Yale Univ. Observatory).
Huang, S.-S. 1953, *Ap. J.*, **118**, 285.
Hutchings, J. B., and Stoeckley, T. R. 1977, *Pub. A.S.P.*, **89**, 19.
Johnson, H. M. 1981, *Ap. J.*, in press.
Koch, R. H., Olson, E. C., and Yoss, K. M. 1965, *Ap. J.*, **141**, 955.
Kraft, R. P. 1965, *Ap. J.*, **142**, 681.
______. 1967*a*, *Ap. J.*, **150**, 551.
______. 1967*b*, *Ap. J.*, **148**, 129.
______. 1970, in *Spectroscopic Astrophysics*, ed. G. H. Herbig (Berkeley: University of California Press), p. 385.
Kreplin, R. W. 1970, *Ann Geophys.*, **26**, 567.
Kreplin, R. W., Dere, K. P., Horan, D. M. and Meekins, J. F., 1977, in *The Solar Output and Its Variation*, ed. O. R. White (Boulder: Colorado Associated Univ. Press), p. 477.
Kron, G. E. 1952, *Ap. J.*, **155**, 301.

Kurucz, R. L., Traub, W. A., Carleton, N. P., and Lester, J. B. 1977, *Ap. J.*, **213**, 771.
Lamers, H. J. G. L. M. 1981, *Ap. J.* **245**, 593.
Levato, O. H. 1972, *Pub. A. S. P.*, **84**, 584.
Levato, H., and Malaroda, S., 1970, *Pub. A. S. P.*, **82**, 741.
Linsky, J. L. 1980, in *Cool Stars, Stellar Systems and the Sun*, ed. A. K. Dupree (Smithsonian Ap. Obs. Special Rept. No. 389)p. 217.
Linsky, J. L., Worden, S. P., McClintock, W., and Robertson, R. M. 1979, *Ap. J. Suppl.*, **41**, 47.
Long, K. S., and White, R. L. 1980, *Ap. J.*, (*Letters*), **239**, L65.
Meadows, A. J. 1961, *M.N.R.A.S.*, **123**, 81.
Mewe, R. 1979, *Space Science Rev.*, **24**, 101.
Mewe, R., and Zwann, C. 1981, in *Cool Stars, Stellar Systems and the Sun*, ed. A. K. Dupree (Smithsonian Astrophys. Obs. Special Rept. No. 389), p. 123.
Milliard, B., Pitois, M. L., and Praderie, F. 1977, *Astr. Ap.*, **54**, 869.
Oke, G. B., and Greenstein, J. L. 1954, *Ap. J.*, **120**, 384.
Palmer, D. R., Walker, E. N., Jones, D. H. P., and Wallis, R. E. 1968, *Bull. Roy. Obs.*, No. 135, E383.
Parker, E. N. 1979, *Cosmical Magnetic Fields* (Oxford: Clarendon Press).
Popper, D. M., and Ulrich, R. K. 1977, *Ap. J. (Letters)*, **212**, 131.
Preston, G. W. 1970, in *Stellar Rotation*, ed. A. Slettebak (New York: Gordon & Breach), p. 254.
Rosendhal, J. D. 1970, *Ap. J.*, **159**, 107.
Rosner, R. 1980, in *Cool Stars, Stellar Systems and the Sun*, ed. A. K. Dupree (Smithsonian Ap. Obs. Special Rept. No. 389), p. 79.
Rosner, R., and Vaiana, G. S. 1980, in *X-Ray Astronomy*, ed. G. Setti and R. Giacconi (Dordrecht: Reidel).
Rucinski, S. M. 1979, *Acta Astr.*, **29**, 339.
Schwarzschild, M. 1958, *Structure and Evolution of the Stars* (New York: Dover).
Seward, F. D., Forman, W. R., Giacconi, R., Griffiths, R. E., Harnden, F. R. Jr., Jones, C., and Pye, J. P. 1979, *Ap. J. (Letters)*, **234**, 55.
Skumanich, A. 1972, *Ap. J.*, **171**, 565.
Slettebak, A. 1949, *Ap. J.*, **110**, 498.
______. 1954, *Ap. J.*, **119**, 146.
______. 1955, *Ap. J.*, **121**, 653.
______. 1956, *Ap. J.*, **124**, 173.
______. 1963, *Ap. J.*, **138**, 118.
______. 1966, *Ap. J.*, **145**, 126.
______. 1970, in *Stellar Rotation*, ed. A. Slettebak (New York: Gordon & Breach), p. 3.
______. 1976, in *Be and Shell Stars*, ed. A. Slettebak (Dordrecht: Reidel), p. 123.
Slettebak, A., Bahner, K., and Stock, J. 1961, *Ap. J.*, **134**, 195.
Slettebak, A., Collins, G. W., II, Boyce, P. B., White, N. M., and Parkinson, T. D. 1975, *Ap. J. Suppl.*, **29**, 137.
Slettebak, A., and Howard, R., 1955, *Ap. J.*, **121**, 102.
Smith, M. A. 1976, *Ap. J.*, **203**, 603.
______. 1978, *Ap. J.*, **224**, 584.
______. 1979, *Pub. A. S. P.*, **91**, 737.
Smith, M. A., and Dominy, J. F. 1979, *Ap. J.*, **231**, 477.
Soderblom, D. R. 1981, *Lick Obs. Bull.*
Struve, O., Sahade, J., Huang, S.-S., and Zebergs, V. 1958, *Ap. J.*, **128**, 310.
Struve, O., and Zebergs, V. 1959, *Ap. J.*, **130**, 783.
Tassoul, J.-L. 1978, *Theory of Rotating Stars* (Princeton: Princeton University Press).
Thomas, R. N. 1981, in *The Stellar Atmosphere*, NASA–CNRS Monograph on Nonthermal Structure of the Solar and Stellar Atmospheres (in press).
Uesugi, A., and Fukuda, I. 1970, *Contrib. Inst. Astrophys. and Kwasan Obs. Univ. Kyoto*, No. 189.
Vaiana, G. S. 1980*a*, *Highlights in Astronomy*, Vol. **5** (Dordrecht: Reidel), p. 419.
______. 1980*b*, in *Cool Stars, Stellar Systems and the Sun*, ed. A. K. Dupree (Smithsonian Astrophys. Obs. Special Rept. No. 389), p. 195.
______. 1980*c*, "X-ray Emission from Stars" presented at the International Symposium on Space Astrophysics, Tokyo, 1980 July.
Vaiana, G. S., *et al.* 1981, *Ap. J.*, **244**, 163.
Vaiana, G. S., and Rosner, R. 1978, *Ann. Rev. Astr. Ap.*, **16**, 393.
van den Heuvel, E. P. J. 1970, in *Stellar Rotation*, ed. A. Slettebak (New York: Gordon & Breach), p. 178.
Vogt, S. S., and Fekel, F., Jr. 1979, *Ap. J.*, **234**, 958.
Wallerstein, G., and Wolff, S. C. 1965, *Pub. A. S. P.*, **77**, 12.
Walter, F. M., and Bowyer, S. 1981, *Ap. J*, in press.
Walter, F., Charles, P., and Bowyer, S. 1980, in *Cool Stars, Stellar Systems, and the Sun*, ed. A. K. Dupree (Smithsonian Astrophys. Obs. Special Rept. No. 389), p. 35.
Watson, R. D. 1972, *Ap. J. Suppl.*, **24**, 167.
White, N. E., Holt, S. S., Becker, R. H., Boldt, E. A., and Serlemitsos, P. J. 1980, *Ap. J. (Letters)*, **239**, L69.
Wilson, O. C. 1966, *Ap. J.*, **144**, 695.
Wilson, O. C., and Skumanich, A. 1964, *Ap. J.*, **140**, 1401.
Zwaan, C. 1977, in *The Sun, a Tool for Stellar Physics*, ed. B. Caccin and M. Rigutti (Erice Summer School), p. 525.
______. 1981, in *Solar Phenomena in Stars and Stellar Systems*, ed. Bonnet and Dupree (Dordrecht: Reidel), in press.

T. R. AYRES: Laboratory for Atmospheric and Space Physics, University of Colorado, Campus Box 392, Boulder, CO 80309

L. GOLUB, R. ROSNER, and G. S. VAIANA: Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

J. L. LINSKY: JILA, University of Colorado, Boulder, CO 80309

R. PALLAVICINI: Osservatorio Astrofisico di Arcetri, Largo Fermi 5, 50125, Firenze, Italy