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The relationship between soft X-rays and the 1640 Å feature fluxes in late-type stars*

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Summary. The λ 1640 feature has been observed in a sample of late-type stars of different luminosity classes. The intensity was measured from IUE low dispersion spectra, and it has been compared with the observed X-ray fluxes, finding a relationship between both quantities for "solar type" stars. The X-ray fluxes derived from this relationship for a reduced sample of stars are consistent with the observed ones in the case of "solar type" stars. "Non solar type" stars exhibit discrepancies that could be explained assuming that the λ 1640 feature is formed by contributers other than He II, which supply an important fraction of this emission in "solar type" stars. The obtained empirical relationship has been used to derive the X-ray flux for some stars that have not been observed in the X-ray range.

Key words: emission lines – X-rays – late type stars

1. Introduction

During the past years stellar outer atmospheres have been studied in a qualitative way from observations of Ca II H and K emission cores, which have shown a differentiated structure similar to the solar atmosphere in late-type stars. Recently, rocket and satellite experiments and mainly the IUE observations have widened our information sources, and they have allowed us to study the Mg h and k emissions and spectral lines emitted from high temperature regions, from which layer models have been derived.

In this context, particular attention has been paid to high temperature lines as C II λ 1335, Si IV $\lambda\lambda$ 1394,1403 C IV λ 1550, He II λ 1640 and N V λ 1240, which cover a temperature range from $2\,10^4$ K to $2\,10^5$ K.

The He II λ 1640 line has been studied in detail, and two formation mechanisms have been proposed for it: collisional excitation (Athay, 1965; Jordan, 1965), indicating a temperature $\simeq 8\,10^4$ K, and recombination following photoionization by coronal X-rays (Zirin, 1976).

Kohl (1977) analyzed the line profile in the Sun, concluding that both mechanisms play a role in the line formation, the collisional excitation being more important in the quiet Sun ($\simeq 70$ %), although its importance decreases in more active regions.

Table 1. Summary of IUE observations

HD	Star	IUE Image	Aperture	Exposure (min)
3712	α Cas	SWP 6697	L	150
10700*	τ Cet	SWP 4054	L	150
12929	α Ari	SWP 6696	L	150
19373*	ι Per	SWP 2663	L	25
20630	κ Cet	SWP 1926	S	35
62509	β Gem	SWP 6659	L	120
114710	β Com	SWP 1901	S	32
140283	......	SWP 2665	L	30
148387*	η Dra	SWP 3597	L	160
161797*	μ Her	SWP 3652	L	20
190248*	δ Pav	SWP 3586	L	120
201091*	61 CygA	SWP 3622	L	120
209100	ε Ind	SWP 6704	L	180
210334	AR Lac	SWP 3777	L	100

*:Processed with the new software.

The connection between the line formation process and the coronal radiation has led Hartmann et al. (1979) to derive a relationship connecting the line intensity and the coronal X-ray flux.

However, the application of this relation presents some difficulties, because in low resolution spectra the observed feature in 1640 Å is a blend of several lines, whose separation is rather complicated because we do not know the quantitative contribution of each one.

In the Sun the Fe II λ 1640.15 line could account for 50 % of 1640 Å intensity (Jordan, 1975; Boland et al., 1975; Kohl, 1977). This contribution varies slightly when regions of different activity are considered.

In this paper we have carried out a study about the 1640 Å feature and the soft X-ray flux, and we have derived a relationship between both (from IUE and HEAO-2 observations), which is

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* Based on observations by the International Ultraviolet Explorer collected at the Villafranca Satellite Tracking Station of the European Space Agency

Table 2. General data for program stars

HD	Star	Spec(a)	V(b)	V-R(b)	π"(a)	[Fe/H](c)	I_k(d)	W_k(km/s)(d)	W_{10830}(e)
3712	α Cas	K0 II-III	2.23	0.78	0.009	——	2	—	0
10700	τ Cet	G8 V_p	3.50	0.62	0.275	-0.34	–	—	–
12929	α Ari	K2 III	2.00	0.84	0.043	-0.08	2	72	0
19373	ι Per	G0 V	4.05	0.53	0.084	-0.01	-	—	–
20630	κ Cet	G5 V	4.64	0.57	0.105	0.08	3	48	0.20
62509	β Gem	K0 III	1.14	0.75	0.093	-0.51	1	74	0.14V
114710	β Com	G0 V	4.26	0.49	0.120	0.27	1	51	0?
140283	——	F5 sd	7.22	0.59	0.037	-1.69	–	—	–
148387	η Dra	G8 III	2.74	0.61	0.043	——	1	65	0
161797	μ Her	G5 IV	3.42	0.53	0.108	0.16	0	—	0.04V
190248	δ Pav	G8 V	3.56	0.61	0.170	0.43	–	—	–
201091	61 CygA	K5 V	5.23	1.03	0.292	-0.06	5	41	0.2V
209100	ε Ind	K5 V	4.69	0.88	0.285	——	–	—	–
210334	AR Lac	K2 III+F8	6.30	——	0.20	-0.30	–	—	–

(a) Hoffleit,1964
(b) Johnson et al,1966
(c) Cayrel de Strobel et al,1980
(d) Wilson,1966
(e) Zirin,1976

compared with the one derived by Hartmann et al., and used to estimate the X-ray flux in a reduced sample, including some stars not observed in X-rays; several stars that have been observed in this range are used mainly as a test of our relationship.

2. Observations

The spectra corresponding to the fourteen late-type stars studied in this paper have been obtained from the IUE data bank. All the spectra have been observed in the low resolution mode and short wavelength range (1150–1950 Å). Instrumental details can be found in Boggess et al. (1978). The corrected Intensity Transfer Function has been used in all the spectra. Some of them have been processed with a new software, providing a better resolution (Bohlin et al., 1981).

The list of IUE images is presented in Table 1. In some of the stars He I λ 10830 and Ca II H and K lines have been observed, showing different activity levels. These results and information about the sample of stars are listed in Table 2.

Linsky and Haisch (1979) plotted in a M_b—(V—R) diagram a sample of late-type stars observed with IUE, finding a boundary line between stars showing high temperature lines and stars in which these lines are very weak or absent. The first group was called "solar type stars" and the other one "non solar type stars". This boundary line joint approximately with the line that marks the onset of large stellar winds.

Recent X-ray observations from HEAO-2 show two differentiated regions in the H – R diagram corresponding with detection or not of soft X-rays. These two regions are approximately the same as suggested by Linsky and Haisch.

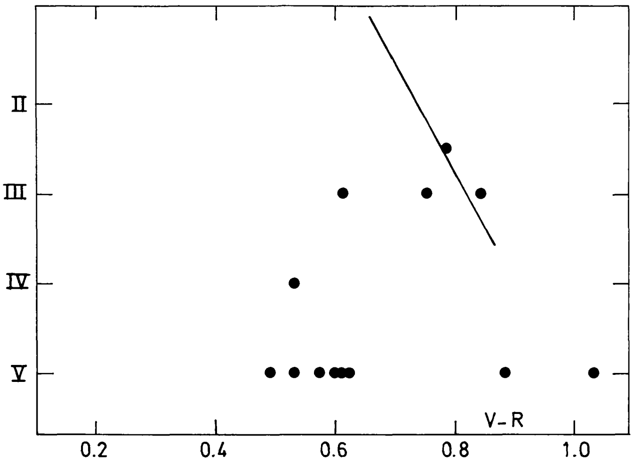

Fig. 1. Diagram of luminosity class, $V-R$ for stars of our sample. The line divides the "solar" and "non solar" regions

In Fig. 1 we have plotted the stars of our sample in the H – R diagram marking out both groups of stars. Only two stars (α Cas and α Ari) lie in the "non solar type" region.

In order to obtain a quantitative indication to separate both types of stars, the observed fluxes corresponding to high tempera-

Table 3. Emission lines and X-ray fluxes

Star	C II λ1335		Si IV λ1394,1403		C IV λ1550		He II λ1640		F_x(a)
	f_λ	$F^*/F_\odot$	f_λ	$F^*/F_\odot$	f_λ	$F^*/F_\odot$	f_λ	$F^*/F_\odot$	
α Cas	0.98	0.10	0.98	0.08	0.48	0.04	0.53	0.19	6.17×10^2
τ Cet	1.93	1.63	0.76	1.19	0.53	0.36	0.06	0.18	1.78×10^4
α Ari	0.25	0.02	0.54	0.09	1.29	0.09	0.46	0.14	4.65×10^2
ι Per	1.17	2.33	1.23	4.57	3.25	5.15	0.35	2.48	2.14×10^4
κ Cet	1.18	4.20	1.99	13.1	2.31	6.50	1.26	15.8	....
β Gem	1.52	0.09	2.65	0.28	3.19	0.15	0.84	0.17	1.29×10^3
β Com	1.46	4.20	2.39	12.5	1.97	4.40	0.34	3.45	2.75×10^5
HD 140283	....	....	....	....	0.12	2.50	0.07	6.40	....
η Dra	0.14	0.06	0.35	0.28	0.46	0.16	0.06	0.11	3.14×10^3
μ Her	0.48	0.55	....	....	0.82	0.74	0.07	0.30	1.74×10^4
δ Pav	0.83	0.78	....	....	0.72	0.54	0.10	0.33	1.25×10^4
61 CygA	0.93	0.73	0.17	0.25	1.35	0.80	1.82	5.06	4.09×10^4(b)
ε Ind	1.93	1.75	....	....	1.06	0.76	0.58	1.85	....
AR Lac	6.39	87	3.15	80	19	205	4.37	211	3.17×10^7(c)

f_λ in 10^{-13} erg. cm.$^{-2}$ s.$^{-1}$

F_x in erg. cm.$^{-2}$ s.$^{-1}$

(a) Vaiana et al, 1981
(b) Pallavicini et al, 1981
(c) observed with HEAO-1, Walter et al, 1980

Table 4. The C IV criterion for activity level classification

Activity level	$F^*/F^{\odot}$ (C IV) λ 1550)	% Recombination	Coronal temperature
Quiet	< 1	30	2 10^6 K
Active	1–10	60	3 10^6 K
Superactive	> 10	80	10^7 K

ture lines – C II λ 1335, Si IV λλ 1394, 1403, C IV λ 1550 and He II λ 1640 – have been measured in each stellar spectrum. These fluxes have been obtained by substracting the continuum due to the photospheric emission and scattered light from longer wavelengths, and integrating the signal across the feature. We have not been able to measure the line flux in a few cases, when the continuum level was not clearly defined or the signal to noise ratio was too low. The corresponding surface fluxes have been derived using the Barnes-Evans relation (1976) and have been related to the values corresponding to the quiet Sun spectrum repported by Linsky et al. (1978).

Results are summarized in Table 3, where observed X-ray fluxes are also shown. These results will be discused later, but now we can remark that they are consistent with the stars location in the H – R diagram.

3. Results

The first attempt to obtain soft X-ray fluxes from the 1640 Å feature was carried out by Hartmann et al. (1979) for two active dwarfs, EQ Pegasi and ξ Bootis A, by means of the relation

$$F_x = CF(\lambda\,1640) \quad (\mathrm{erg\ cm^{-2}\ s^{-1}}) \qquad (1)$$

based in previous works of Raymond et al. (1979) and in the theoretical X-ray spectrum of Raymond and Smith (1977). A value of $C \simeq 50$ for coronal temperatures between 10^6 K and 2.5 10^6 K was derived. $F(\lambda\,1640)$ correspond to the total intensity of the 1640 Å feature. Therefore, the Fe II contribution is taken into account jointly with the He II one, and this could be an important error source for several reasons. First of all, X-ray fluxes depend only on the He II intensity, and on the other hand the unknown Fe II fraction is related to the iron abundance, that is expected to change for each star. However, a good agreement was found between derived and observed X-ray fluxes in "solar type" stars. Nevertheless, important differences between values computed from relation (1) and observations appear in the case of the supergiants αAqr and βAqr, analyzed by Hartmann et al. (1980). The most immediate way to explain this discrepancy is by assuming that in these stars the 1640 Å feature is due mainly to other elements than He II, according to Linsky and Haisch (1979), who assumed that in "non solar type" stars the 1640 Å feature is in a large fraction originated by Fe II, and He II is absent. Another factor to take into account is the presence of circumstellar material, that could attenuate the X-ray emission.

We have attempted to estimate the Fe II contribution to the 1640 Å blend. Contribution by other elements appears to be less important, as solar high resolution spectra show. In the Sun, the main contributer to the blend, with He II, is Fe II λ 1640.15,

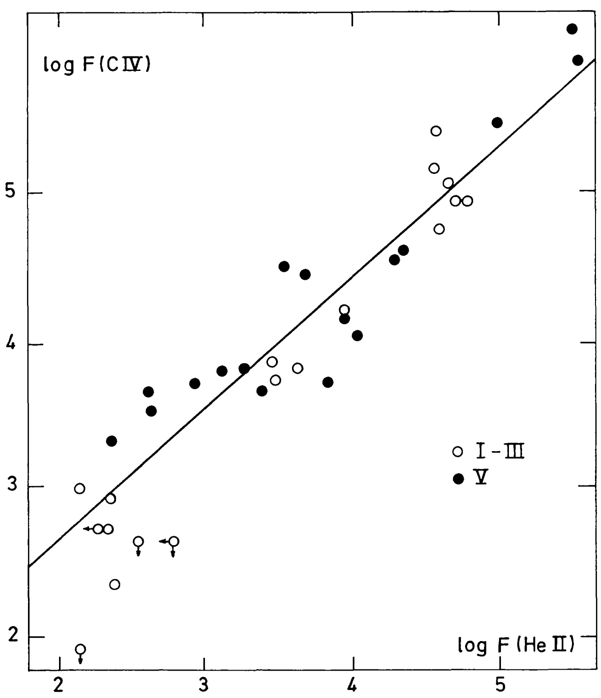

Fig. 2. C IV λ 1550 and λ 1640 surface fluxes for the widened sample of stars

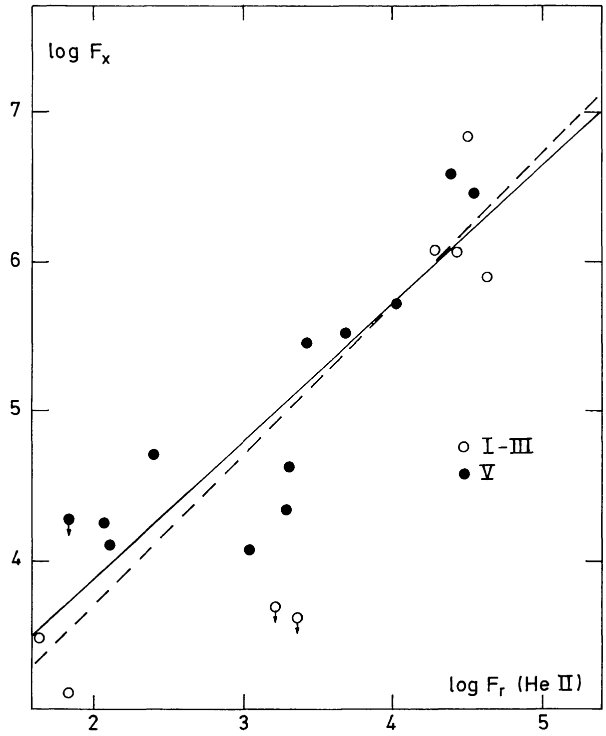

Fig. 3. X-ray observed fluxes as a function of the He II recombination fraction

belonging to multiplet 43. We have tried to identify another line of the same multiplet, λ 1612.8, but it is rather masked in all cases. According to Linsky and Haisch (1979), in "non solar type" stars the blend could be due to Fe II λλ 1637.4, 1640.9 (multiplet 42). Another line belonging to the same multiplet is λ 1649.4, but its weakness and the low signal to noise ratio attainable in this spectral region have made impossible the measurement of reliable values of its intensity.

Although all the authors recognize the importance of an accurate determination of the Fe II contribution to the 1640 Å blend, this is not possible in low resolution mode. Therefore we are bound to use the 1640 Å feature without any correction, and we will discuss later how the Fe II contribution can act upon results.

Our goal is to derive from observations a relationship between the λ 1640 feature intensity and the soft X-ray flux for late-type stars. But we must take into account that recombination following photoionization is not the only mechanism in the He II Bα line formation. The collisional excitation mechanisms can play an important role. However, only the fraction of intensity originated by recombination is directly related to the X-ray emission.

High resolution spectra analysis of different solar regions show that both mechanisms are present in all cases, but in different proportions depending on the activity level. The intensity fraction due to recombination is 30 %, 60 %, and 80 % in the quiet, active and superactive Sun, respectively. This classification is correlated with the C IV λ 1550 line intensity in the different solar regions. On the basis of this C IV sensitivitvy to the activity level, Hartmann et al. (1982) have elaborated a criterion to classify stars into three categories (quiet, active and superactive) using the ratio between the C IV stellar surface flux to the quiet Sun.

In a similar way, we have carried out the classification of our program stars, as shown in Table 4.

In Fig. 2 we have plotted the C IV and He II surface fluxes for a widened sample of late-type stars, including observed values collected from literature (Ayres et al., 1981; Hartmann et al., 1982). The data have been fitted by a line, obtaining a correlation coefficient of 0.95. The corresponding relationship is given by

$$F(\mathrm{C\,IV}) = 7.45 \quad F(\mathrm{He\,II})^{0.89} \quad (\mathrm{erg\,cm^{-2}\,s^{-1}}). \tag{2}$$

Inspection of Fig. 2 indicates a similar behaviour between dwarfs and giants.

In Fig. 3, X-ray surface fluxes are plotted as a function of the photoionization fraction of the He II surface flux. This fraction has been obtained from the classification of each star in one of the three degrees of activity. As in the above case we have plotted the widened sample. The solid line represents the best fit, corresponding to a correlation coefficient of 0.92, leading to the following relation

$$F_x = 90 \; F_r(\mathrm{He\,II})^{0.94} \quad (\mathrm{erg\,cm^{-2}\,s^{-1}}), \tag{3}$$

where F_r is the recombination fraction of the He II surface flux. We note that in all cases F(He II) correspond to the 1640 Å feature total emission, including an undetermined fraction of Fe II. The accuracy of this assumption depends on the different iron contributions in the considered stars. We have also plotted the relation (1) by a dashed line. The difference between both, solid and dashed, lines is within the error bars corresponding to the least squares fit.

We note that relation (1) (with $C \simeq 50$) was derived for a limited range of coronal temperatures, while no restricting assumptions have been stablished to obtain relation (3).

From relation (3) we have computed the X-ray surface fluxes for some of the program stars. Some of these stars have been observed in X-rays, and we will compare the derived results with

Table 5. X-ray luminosities and emission measure for selected stars

Star	Activity level	log L_x (a)	log L_x (b)	log L_x (obs.)	log E.M.
α Cas	Quiet	30.21	30.07	29.30	52.84
α Ari	Quiet	28.84	28.69	27.90	51.47
κ Cet	Active	28.62	28.61	26–30	51.05
HD 140283	Active	28.30	28.27	28.5–30.5	50.73
ε Ind	Quiet	27.19	27.10	27–29	49.82
AR Lac	Superactive	30.65	30.71	31.17	53.08

(a) Computed from relation (3)
(b) Computed from relation (1)
L_x in erg s^{-1}
E.M. in cm^{-3}

observations. Obviously, none of these stars have been used in deriving relation (3).

The emission measure has been computed too, from the calculated X-ray luminosity and the theoretical spectrum of Raymond and Smith (1977). Following the above criteria, a coronal temperature has been assigned to each star according to its activity level. These temperatures are 2 10^6 K, 3 10^6 K, and 10^7 K for quiet, active and superactive stars, respectively.

In Table 5, L_x values found from relation (1) and (3) are listed. As can be seen, discrepancies between values obtained from both relations are rather small in all cases. The observed L_x and the emission measure are presented too. As εInd, HD 140283 and κCet have not been observed in the X-ray range, the values listed in the "observed L_x" column correspond to the upper and lower limits observed in stars of the same spectral type and luminosity class. Inspection of the results show that computed values are within these limits for εInd and κCet. However, the obtained value for HD 140283 is slightly out of the limits, but taking into account the inherent error of the process the discrepancy is not significant.

The AR Lacertae system present a calculated value of L_x lower than the observed one. In this case the small difference can be explained in a similar way. A higher disagreeement between theoretical and observational values of L_x is shown by αCas and αAri, classified as "non solar type" stars because of their location in the H – R diagram. This agrees with the low fluxes of the high temperature lines in both stars, as can be seen in Table 3. These stars show a derived X-ray luminosity higher than the observed one by a factor of 8. This discrepancy can be understood considering that the 1640 Å blend in these stars has Fe II as main contributer, instead of He II.

In "solar type" stars the observed scatter in Fig. 3 could be caused by differences in the stellar iron abundances, that can affect the Fe II fraction of intensity in the 1640 Å blend. In any case, the scatter is not very large, suggesting a weak influence of Fe abundance in our empirical relationship for "solar type" stars.

We point out that the coronal temperature restriction from which relation (1) with $C \simeq 50$ was derived can be obviated in the "solar type" case.

4. Conclusions

In this paper we have studied the relationship between the soft X-ray flux and the λ 1640 feature intensity in a sample of late-type stars, under the following assumptions:

a) Due to the impossibility to deblend the He II Bα line from other contributers (mainly Fe II) in the available low resolution spectra, we have considered that all the observed feature intensity comes from the helium line, and

b) Only the fraction of the He II line due to recombination is directly related to the X-ray flux. We have assumed that for each star this fraction varies with the activity level in a similar way as it does in different solar regions.

We have found a close correlation between both, λ 1640 and X-ray, fluxes for "solar type" stars. This relation is independent of the luminosity class, and it is valid for stars with rather different coronal temperatures. This indicates that our assumptions are not far from reality. Fe II contribution to the λ 1640 blend could be negligible, except in the "non solar type" stars, where this ion can be the main contributer to the line intensity. The application of relation

$$F_x = 90\ F_r(\mathrm{He\,II})^{0.94}$$

in this case would lead to erroneous results.

References

Athay, R.G.: 1965, *Astrophys. J.* **142**, 755

Ayres, T.R., Marstad, N.C., Linsky, J.L.: 1981, *Astrophys. J.* **247**, 545

Ayres, T.R., Linsky, J.L., Vaiana, G.S., Golub, L., Rosner, R.: 1981, *Astrophys. J.* **250**, 293

Barnes, T.G., Evans, D.S.: 1976, *Monthly Notices Roy. Astron. Soc.* **174**, 489

Boggess, A., Carr, F.A., Evans, D.C., Fischel, D., Freeman, H.R., Fuechsel, C.F., Klinglesmith, D.A., Krueger, V.L., Longanecker, G.W., Moore, J.V., Pyle, E.J., Rebar, F., Sizemore, K.O., Sparks, W., Underhill, A.B., Vitagliano, H.D., West, D.K., Macchetto, F., Fitton, B., Parker, P.J., Dunford, E., Gondhalekar, P.M., Hall, J.E., Harrison, V.A.M., Oliver, M.B., Sandford, M.C.V., Vaughan, P.A., Ward, A.K., Anderson, B.E., Boksenberg, A., Coleman, C.I., Snijders, M.A.J., Wilson, R.: 1978, *Nature* **275**, 377

Bohlin, R.C., Holm, A.V., Lindler, A.J.: 1981, IUE ESA *Newsletter* **10**, 10

Boland, B.C. et al.: 1975, *Monthly Notices Roy. Astron. Soc.* **171**, 697

Brown, A., Jordan, C.: 1980, *Monthly Notices Roy. Astron. Soc.* **191**, 37P

Cayrel de Strobel, G., Bentolila, C., Hauck, B., Curchod, A.: 1980, *Astron. Astrophys. Suppl.* **41**, 405

Hartmann, L., Davis, R., Dupree, A.K., Raymond, J., Schmidtke, P.C., Wing, R.F.: 1977, *Astrophys. J. Letters* **233**, L69

Hartmann, L., Dupree, A.K., Raymond, J.C.: 1980, *Astrophys. J. Letters* **236**, L143

Hartmann, L., Dupree, A.K., Raymond, J.C.: 1982, *Astrophys. J.* **252**, 214

Hoffleit, D.: 1964, Catalogue of Bright Stars, Yale University Press

Johnson, H.L., Mitchell, R.G., Iriarte, B., Wisniewsky, W.Z.: 1966, *Comm. Lunar and Planetary Lab.* **4**, 99

Jordan, C.: 1975, *Monthly Notices Roy. Astron. Soc.* **170**, 429

Kohl, J.L.: 1977, *Astrophys. J.* **211**, 958

Linsky, J.L., Ayres, T.R., Basri, G.S., Morrison, N.D., Boggess, A., Schiffer, F.H. III, Holm, A., Cassatella, A., Heck, A., Macchetto, F., Stickland, D., Wilson, R., Blanco, C., Dupree, A.K., Jordan, C., Wing, R.F.: 1978, *Nature* **275**, 389

Linsky, J.L., Haisch, B.W.: 1979, *Astrophys. J. Letters* **229**, L27

Raymond, J.C., Noyes, R.W., Stopa, M.P.: 1979, *Solar Phys.* **61**, 271

Raymond, J.C., Smith, B.W.: 1977, *Astrophys. J. Suppl.* **35**, 419

Pallavicini, R., Golub, L., Rosner, R., Vaiana, G.S., Ayres, T., Linsky, J.L.: 1981, *Astrophys. J.* **248**, 279

Vaiana, G.S., Cassinelli, J.P., Fabbiano, G., Giacconi, R., Golub, L., Gorenstein, P., Haisch, B.M., Harnden, F.R., Johnson, H.M., Linsky, J.L., Maxson, C.W., Meve, R., Rosner, R., Seward, F., Topka, K., Zwaan, C.: 1981, *Astrophys. J.* **245**, 163

Walter, F.M., Cash, W., Charles, P.A., Bowyer, C.S.: 1980, *Astrophys. J.* **236**, 212

Wilson, O.C.: 1966, *Astrophys. J.* **205**, 803

Zirin, H.: 1975, *Astrophys. J. Letters* **199**, L63

Zirin, H.: 1976, *Astrophys. J.* **208**, 414