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ULTRAVIOLET AND VISIBLE FLARE OBSERVATIONS OF EQ PEGASI B

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ABSTRACT

EQ Peg AB (dM4e + dM5.5e) was monitored in the visible at the Whipple Observatory and ultraviolet with *IUE* on 1981 September 2. In the visible spectrophotometry of EQ Peg B the Hβ emission strengthened by a factor of 2 relative to the nearby stellar continuum within a few minutes and decayed over an hour. This flare in EQ Peg B was coincident with the enhancement of ultraviolet emission lines of C IV λ1550, He II λ1640, and C II λ1335 in the combined light of EQ Peg AB. The ultraviolet fluxes during the flare can be interpreted as similar to those either in the thermal phases of large two-ribbon solar flares where radiative cooling balances thermal conduction or in gas cooling quickly from X-ray emitting temperatures. The appearance of the ultraviolet continuum at λλ1700–1900 and ratio of Hα to Hβ fluxes during the flare are consistent with models producing these emissions in the chromosphere.

Subject headings: stars: flare — stars: individual — ultraviolet: spectra

I. INTRODUCTION

EQ Peg is a visual binary with both stellar components UV Ceti–type or dMe flare stars. The spectral types are dM4e + dM5.5e, with brightnesses of $V = 10.4$ mag and 12.6 mag and a separation of 3″.7 (Kukarkin 1969). The combined flaring rate for both components is about one large flare every 1.3 hr in the *U* passband (Lacy, Moffett, and Evans 1976), although the fainter star is probably more active. Flares as energetic as 10^{32} ergs have been observed in the *U* passband for EQ Peg AB, and on other dMe stars energies of up to 10^{34} ergs have been observed (Lacy, Moffett, and Evans 1976).

Observations of stellar flares are important because they serve to refine theoretical models that rely on stellar magnetic phenomena. Stellar flares have been successfully monitored in many wavelength regions, for example in the X-ray and visible in YZ CMi (Kahler *et al.* 1982) and X-ray, visible, and ultraviolet in Proxima Cen (Haisch *et al.* 1983). These coordinated efforts test theories of heating of the flare atmosphere by X-radiation (cf. Haisch 1983). In the ultraviolet, observations can, as demonstrated by both solar and stellar flare results (cf. Machado and Emslie 1979), eliminate many of the models of distribution of the flare energy. The dependence of density and emission measure distribution on flare luminosity can be examined and the nature of the flare continuum can be explored.

II. OBSERVATIONS

The star EQ Peg B was monitored on 1981 September 2 in the ultraviolet with the *IUE* satellite and in the visible with the 1.5 m telescope at the F. L. Whipple Observatory. A summary of the spectrum observations appears in Table 1.

In the ultraviolet, low-dispersion (about 6 Å resolution), short- and long-wavelength spectra were obtained. The short-wavelength spectra were exposed in pairs on both sides of the large aperture with 15–30 minute integrations. The absolute flux calibration was that of Bohlin and Holm (1980). Details of the *IUE* satellite performance are given by Boggess *et al.* (1978*a*, *b*).

The ground-based data were obtained with the medium-dispersion spectrograph and intensified, photon-counting Reticon array (Tonry and Davis 1979). The spectra have a resolution of about 6 Å and cover the wavelength range λλ4700–7000. In order to obtain spectrophotometry of EQ Peg B, we used the 2″.6 apertures and monitored the standard star EG 139 (= Wolf 1346, dA). The dual-slit spectrograph simultaneously accumulates the sky background in addition to the stellar spectrum. The instrumental response has been removed by the flat-field produced by an incandescent light source. The wavelength calibration is described by a seventh-order polynomial fit to He-Ne-Ar emission-arc spectra bracketing each stellar exposure. From the calibration of the standard star EG 139 (Oke 1974) we inferred the stellar flux of the visible spectrum of EQ Peg B outside the Earth's atmosphere. Emission lines of Hα and Hβ along with strong absorption edges of TiO bands are prominent features of the spectra (Fig. 1).

TABLE 1

SUMMARY OF VISIBLE AND ULTRAVIOLET SPECTRA OF EQ PEGASI 1981 SEPTEMBER 2

A. *IUE*—Ultraviolet

IUE Sequence No.	Exposure Time (min.)	U.T. at Mid-Exposure (hr)
SWP 14879L[a]	15	8.4
SWP 14879R	15	8.8
LWR 11455	25	9.4
SWP 14880L	30	10.0
SWP 14880R	30	10.3
LWR 11456	25	11.1
SWP 14881L	30	11.7
SWP 14881R	30	12.3
LWR 11457	25	12.8
SWP 14882L	30	13.4
SWP 14882R	30	14.0

B. Whipple Observatory—Visible

Sequence Number	Exposure Time (min.)	Range of U.T. (hr)
ZD 5448–5464	10	8.3–12.8

[a] "L" and "R" are arbitrarily assigned to distinguish sequential spectra on the "left" or "right" side of the aperture in a given image.

[1] Guest Observer, *International Ultraviolet Explorer* Satellite (*IUE*).

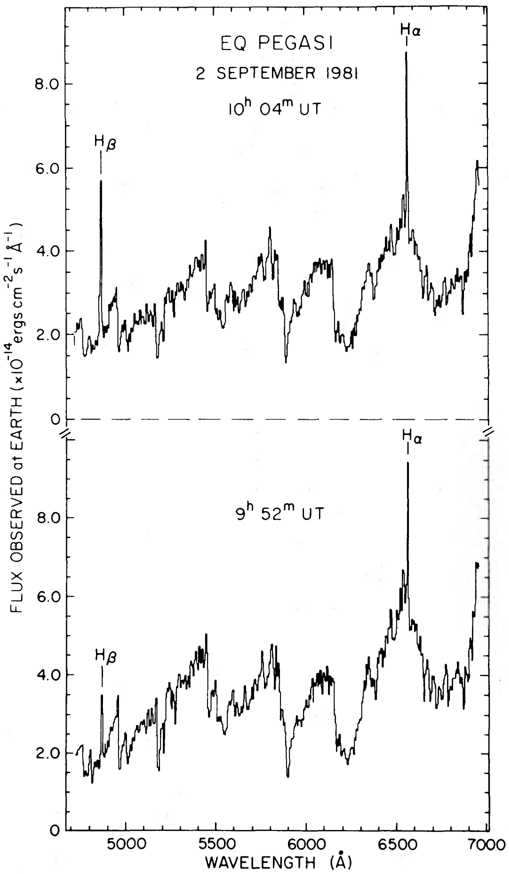

FIG. 1.—Visible spectrophotometry of EQ Peg B before (*lower panel*) and during (*upper panel*) the flare on 1981 September 2. Hβ increases by about a factor of 2 and Hα increases only marginally, about 20%.

The brighter companion (3".7 distant) was excluded from the visible observations by the small 2".6 apertures. Separate spectra of EQ Peg A in the visible reveal Balmer emission of smaller equivalent width than in EQ Peg B. In the ultraviolet spectra, the stars are not resolved because their spatial separation is comparable to the camera resolution (3") and smaller than the slit width (10"). The fluxes in the ultraviolet undoubtedly contain contributions from both components. Judging from the strength and behavior of the chromospheric emission in the visible spectra, we conclude that EQ Peg B dominates the chromospheric and coronal emission in the ultraviolet during the flare. No attempt has been made here, however, to separate the quiescent flux contributions from both stars.

At about 1030 UT on September 2, a flare was detected in both the ultraviolet and visible spectra. The strength of the Hβ emission doubled relative to the nearby photospheric continuum while Hα emission increased slightly as early as 10:02 UT (Fig. 1). In the ultraviolet short-wavelength spectra, emission lines of C IV λ1550, Si IV λ1400, N V λ1240, He II λ1640, and C II λ1330 were prominent during the flare (Fig. 2). The C IV emission increased dramatically—over a factor of 3 enhancement was observed. The $\lambda\lambda$1700–1900 continuum brightened above detection threshold. In the long-wavelength ultraviolet spectra, Mg II $h+k$ (λ2800) may have increased as much as 10% compared to the faintest measurement, but the LWR exposure missed the brightest part of the flare. The Fe II emission complex $\lambda\lambda$2600–2650 is weak but may also have strengthened in the flare by as much as 20%.

The fluxes of ultraviolet and visible emission lines are given in Table 2 for the flare and compared with the averages of the emission strengths for pre- and postflare spectra, along with the calculated standard deviation of the mean for the nonflaring spectra. These standard deviations indicate a lower limit to the significance of relative enhancements during the flare for the ultraviolet emission lines. The indicated uncertainties are conservative upper limits for two reasons: first, the flare emissions have higher signal-to-noise ratios, and second, less obvious flaring activity in the presumed quiescent state may contribute to the scatter. For the Hα and Hβ emission strengths, the error is derived from the photon statistics. This estimate of the precision is also conservative as indicated from the following. We measured the equivalent width of an absorption feature between $\lambda\lambda$5170 and 5120, to quantify the precision and to discern any variations in the stellar continuum. The standard deviation from the mean of the equivalent widths is about 2%, comparable to the error derived from photon statistics propagated through the equivalent width calculation. The precision in the Hα and Hβ fluxes is given by the photon statistics of an individual measurement and should be a good estimate of the relative flux variations in Hα and Hβ. Although Hβ brightens significantly during the flare, Hα does so only marginally.

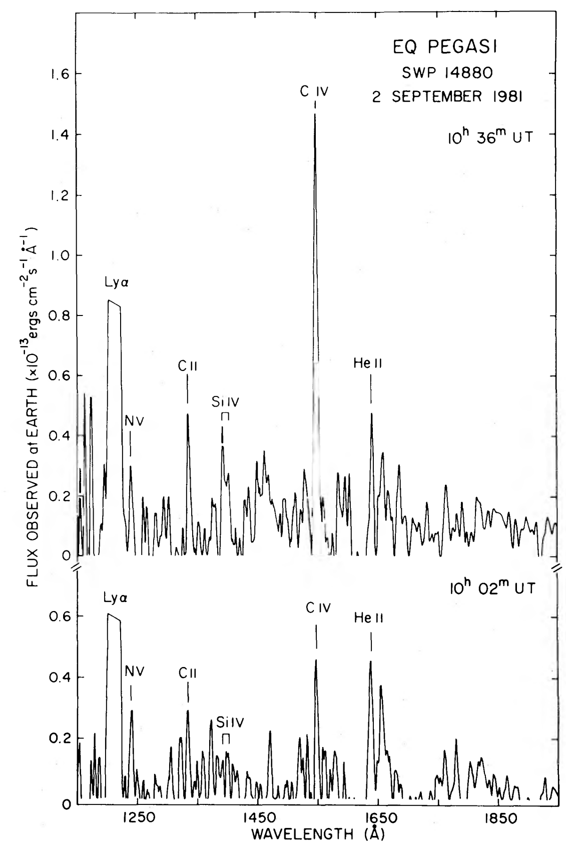

FIG. 2.—Spectra of EQ Peg AB from *IUE* coincident with the flare on EQ Peg B in the visible. Note the enhancement of C IV λ1550, Si IV λ1400 and C II λ1335 during the flare (*upper panel*), but the strengthening of He II λ1640 prior to maximum enhancement of C IV λ1550 (*lower panel*). Both of these spectra are coincident with bright Hα and Hβ emission.

TABLE 2

Flare and Quiescent Emission-Line Fluxes from EQ Pegasi B 1981 September 2

		f_0 ($\times 10^{-13}$ erg cm^{-2} s^{-1})[a]			
Feature	λ(Å)	Quiescent[b]	Flare + Quiescent[c]	Flare Only	Maximum Std. Deviation (%)[d]
N v	1240	1.7	2.1	0.5	3
C ii	1330	1.6	2.7	1.1	10
Si iv	1394	...	5.0	(5)	...
C iv	1550	2.6	9.5	6.9	6
He ii	1640	0.9	3.0[e]	2.1[e]	15
O iii	1663	...	2.0	(2)	...
Continuum	1765–1885	<0.2	0.6	(0.4)	...
Fe ii	2600–2650	850	995	145	3
Mg ii ($h+k$)	2795–2802	1640	1730	90	3
Hβ	4861	1.6	3.2	1.6	7
Hα	6563	3.5	4.5	1.0	4

[a] Flux observed at Earth.

[b] The quiescent ultraviolet fluxes are the sum of fluxes from EQ Peg A and B. The ultraviolet measurements are the averages observed from the sum of the left- and right-aperture spectra SWP 14879, SWP 14881, SWP 14882, along with 14880L. The Fe ii and Mg ii fluxes are averages from LWR 11455 and LWR 11457. Hα and Hβ are averages exclusive of those between 10.0 and 10.5 UT.

[c] The flare plus quiescent fluxes are from SWP 14880R and LWR 11456. Hα and Hβ are averages between 10.0 and 10.5 UT.

[d] Percent standard deviation of the mean of the quiescent level fluxes.

[e] The peak He ii flux is from SWP 14880L and is brighter just prior to the flare than during it. See text.

The fluxes in the ultraviolet and visible as a function of time are shown in Figure 3.

III. DISCUSSION

Although both stars probably contribute to the preflare ultraviolet fluxes, the flare fluxes alone are obtained by subtracting the presumed "quiescent" levels. The flare almost certainly arises from EQ Peg B because the large C iv enhancement is contemporaneous with the Hβ and Hα increases observed on component B.

The ultraviolet fluxes in the quiescent state from both components differ somewhat, even considering the observational uncertainties, from those observed by Hartmann, Dupree, and Raymond (1982). For example, N v was fainter, and C ii and C iv brighter, in the 1979 Hartmann *et al.* spectra. It is likely that chromospheric and coronal variations cause these differences.

The flare fluxes, corrected for the quiescent levels, appear in Table 2. The behavior of He ii λ1640 as a function of time is noteworthy: the peak flux of He ii occurs in the exposure prior to the peak of C iv λ1550 emission strength. The midexposure time of the ultraviolet spectrum with maximum He ii flux is coincident with the beginning of the flare in Hα and Hβ. Thus the enhancement of He ii could have occurred at the earliest about 15 minutes before the brightening of Hα and Hβ.

To interpret the line emission during the flare we assume the flare to be a magnetic loop or series of loops (cf. Rosner, Tucker, and Vaiana 1978). This model fails for compact solar flares and for the impulsive phases of large flares, but it does represent the thermal phases of large two-ribbon solar flares (cf. Withbroe 1978). In most of the loop, radiative cooling balances thermal conduction heating. For a cooling coefficient proportional to $T^{-1/2}$ (a good approximation in the temperature range $T \sim 10^5$ to 2×10^7 K), the logarithmic emission measure is proportional to $T^{1.5}$. This is in reasonable agreement with empirical emission measure curves of solar flares (Withbroe 1978; Doyle and Raymond 1983).

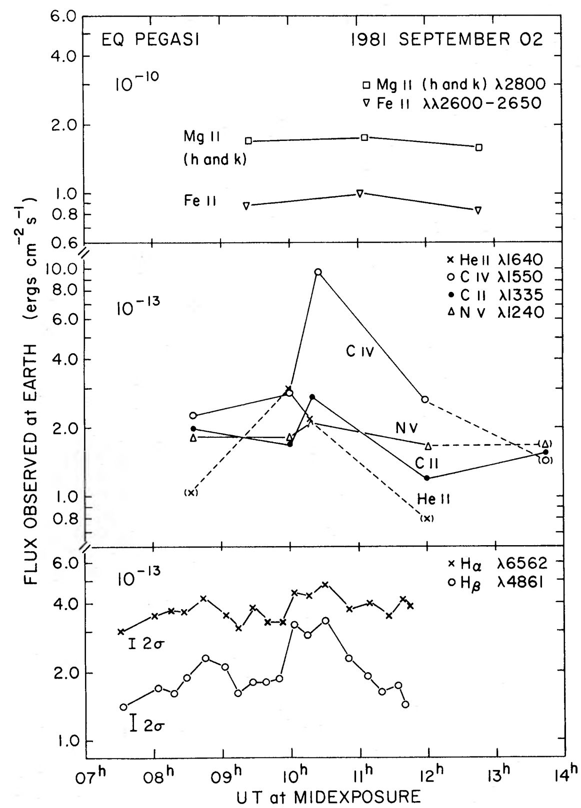

Fig. 3.—Fluxes outside the Earth's atmosphere as a function of time at midexposure in EQ Peg AB on 1981 September 2. The *IUE*-ultraviolet Mg ii and Fe ii fluxes are shown in the upper panel, and the short-wavelength spectrum fluxes in the middle panel. The Hα and Hβ fluxes are shown in the lower panel. The ultraviolet emission is likely the combined light from EQ Peg AB, but the visible and flare emission from EQ Peg B only. The ordinate of each plot should be multiplied by the factor shown in the upper left of the panel.

TABLE 3

PREDICTED He II/C IV EMISSION FOR FLARE LOOP MODEL

log T_{max}	Flux Ratio He II(λ1640)/C IV(λ1550)
6.0	0.063
6.2	0.13
6.4	0.15
6.6	0.17
6.8	0.20
7.0	0.29
7.2	0.44
7.4	0.60

We will also assume that the He II λ1640 line emission is dominated by recombination following photoionization of He^+ by coronal EUV photons (54 eV < $h\nu$ < 100 eV; Hartmann *et al.* 1979; Hartmann, Dupree, and Raymond 1982). Seely and Feldman (1984) have recently interpreted solar observations of λ1640 line profiles as indicating that excitation in the transition region accounts for a greater fraction of the λ1640 than was estimated by Hartmann *et al.* (1979). However, the neglect of collisions among the $n = 3$ levels in the Seely and Feldman calculations, which is valid for quiet Sun densities at temperatures near 10^5 K, is not valid at $T \sim 10^4$ K, where the recombination component originates. Under flare conditions, it is not valid at any temperature. Since the Seely and Feldman estimates for the recombination contribution cannot account for the strength of the narrow component of the λ1640 feature in the high spectral resolution observations reported by Kohl (1977), we use the Hartmann *et al.* estimates, attributing nearly all of the λ1640 emission during the flare to recombination following photoionization by coronal EUV photons. This assumption is supported by the excellent agreement of X-ray and ultraviolet observations of a flare on Proxima Cen with this model (Haisch *et al.* 1983). Table 3 gives predicted ratios of He II λ1640 to C IV λ1550 for loops of maximum temperature T_{max} computed according to Raymond and Doyle (1981). A model with log T_{max} = 6.8–7.0 agrees with the observed ratio of the time-integrated fluxes. Solar flares generally reach peak temperatures somewhat higher than this, but the temperature declines during the course of the flare. This behavior of the temperature of solar flares is consistent with the temperature of the EQ Peg B flare inferred from the very high He II/C IV ratio in the exposure at 10.0 UT and the lower ratio in the subsequent spectrum. However, the 10.0 exposure may include an impulsive phase which cannot be described by the static loop models.

The parallax of EQ Peg, $\pi = 0''.155$ (Gliese 1969), implies a distance of 6.4 pc. The λ1640 luminosity and the model for production of He II recombination emission (Hartmann, Dupree, and Raymond 1982) then imply an X-ray energy of 6×10^{32} ergs.

The lifetime of the flare was about 30 minutes in Hβ and no more than that in the ultraviolet lines, similar to the duration of the flare on Proxima Cen described by Haisch *et al.* (1983). Thus, the inferred X-ray luminosity would be $\sim 3 \times 10^{29}$ ergs s^{-1} and the emission measure $\sim 1.5 \times 10^{52}$ cm^{-3}. Stern, Underwood, and Antiochos (1983; cf. Haisch 1983) suggest scaling relations under the assumption that the flare decay time, the radiative cooling time, and the conductive cooling time are all about equal, as is generally observed in large solar flares. These relations imply a temperature $T \sim 7 \times 10^7$ K, an electron density $n_e \sim 2 \times 10^{11}$ cm^{-3}, a length $L \sim 5 \times 10^{10}$ cm. If the X-ray flare decayed more quickly than the Balmer line emission, the electron density would be larger and length of the loop smaller.

There is some evidence that a significant part of the ultraviolet line emission in a large solar flare comes from gas which is heated to X-ray emitting temperatures, then cools when the heating ceases (Doyle and Raymond 1983). A constant density cooling calculation by Doyle *et al.* (1983) yields 8 eV emitted in the C IV doublet for every H atom in the cooling gas. Thus, an emission measure of 1.5×10^{52} cm^{-3} and $n_e \sim 2 \times 10^{11}$ cm^{-3} imply a C IV luminosity from the cooling gas of 1×10^{30} ergs, or about 10%–15% of the observed C IV emission. The N V emission is predicted to be about one-seventh of C IV, consistent with the observed value and its uncertainty.

Table 4 lists the enhancements observed during stellar flares recorded by *IUE* to date. The maximum enhancements occur near temperatures of 10^5 K and just below. For example, C IV ($T \sim 1 \times 10^5$ K) always brightens more than N V (2×10^5 K). The differential emission measure curve for solar flares (Machado and Emslie 1979) shows a rapid decrease with increasing temperature in this temperature range, in agreement with the preferential brightening of C IV relative to N V.

The appearance of continuous emission in the ultraviolet at $\lambda\lambda$1700–1900 during the flare (see Fig. 2) has implications for theories of stellar flares. A similar continuum was observed for the flare in Gliese 867A (Butler *et al.* 1981). Models of solar and stellar flares generally indicate that the ultraviolet continuum and Balmer line emission arise in the chromosphere at temperatures around 10,000 K. A model with parameters appropriate for flare stars (Katsova, Kasovichev, and Livshitz 1981) predicts $T \sim 9000$ K for the optical continuum. If we assume that Hα and Hβ are formed in LTE at a single temperature, their ratio suggests $T = 6900$ K. Since Hα has a higher opacity it is formed at higher temperature, so 6900 K is a lower limit. The shape of the ultraviolet continuum between 1600 Å and 1900 Å is consistent with Kurucz (1979) models of 9000 K atmospheres, but the uncertainties are large. If the actual duration of the continuum event is t, the emitting area is $\sim 2 \times 10^{18}$ (30 minutes/t) cm^2, comparable in size to a moderately large solar flare. If we take 9000 K as the effective temperature of the

TABLE 4

ULTRAVIOLET EMISSION ENHANCEMENTS IN STELLAR FLARES RELATIVE TO QUIESCENT LEVELS

Feature	λ (Å)	log T_{max} (K)	λ And[a]	Prox Cen[b]	UX Ari[c]	Gliese 867A[d]	EQ Peg B
He II	1640	>5.3	1.4	3.5	...	1.3	3.3
N V	1240	5.3	1.9	4.8	6.1	1.3	1.2
C IV	1550	5.1	3.0	6.8	...	2.2	3.6
Si IV	1400	4.9	2.4	...	5.4	1.2	(>5)
C III	1175	4.7	4.6	...	5.8	...	...
C II	1335	4.3	2.1	>3.1	...	2.1	1.7
Lyα	1215	4.3	3.2[e]	...	...	...	...
Mg II	2795 2802	3.9	1.17	...	...	...	1.05
C I	1660	3.85	1.2	...	...	1.2	...
	1560	3.85	...	3.2	...	...	...
Si II	1808 1817	3.8	1.3	~1.7	5.5	1.7	...

[a] Baliunas *et al.* 1984.
[b] Haisch *et al.* 1983.
[c] Simon *et al.* 1980.
[d] Butler *et al.* 1981.
[e] Corrected for geocoronal emission.

flare continuum, the chromospheric luminosity was about 5 times the X-ray luminosity inferred above. While both luminosities are uncertain, this suggests that X-ray illumination of the chromosphere (Machado, Emslie, and Brown 1978) cannot account for the observed chromospheric heating.

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