THE ASTROPHYSICAL JOURNAL, 263:269–276, 1982 December 1

ULTRAVIOLET AND X-RAY DETECTION OF THE 56 PEGASI SYSTEM (K0 IIp + WD): EVIDENCE FOR ACCRETION OF A COOL STELLAR WIND ONTO A WHITE DWARF

M. SCHINDLER, R. E. STENCEL,[1] AND J. L. LINSKY[2]
Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards
G. S. BASRI[1]
Department of Astronomy, University of California at Berkeley
AND
D. J. HELFAND
Columbia Astrophysical Laboratory, Columbia University
Received 1982 February 1; accepted 1982 June 7

ABSTRACT

IUE spectra of the slowly rotating mild barium star 56 Peg (HD 218356; K0 IIp) show excess continuum emission from 1300 to 2000 Å, a broad Lyα absorption feature, and emission lines usually associated with a 10^4–(2×10^5) K plasma. The best fit blackbody curve to the dereddened continuum gives a temperature of $32{,}000 \pm 4000$ K and a radius for the object of $(2.7 \pm 1.0) \times 10^9$ cm, consistent with that of a white dwarf. *Einstein* IPC observations of this system yield $L_x \approx 3 \times 10^{31}$ ergs s^{-1}, which is as bright as the RS CVn binary systems. The X-rays can be fitted to a bremsstrahlung spectrum with $kT = 0.45 \pm 0.3$ keV, or a blackbody spectrum with $kT \approx 0.2$ keV. Since bright X-ray and high temperature emission lines are unusual for single stars in this region of the H-R diagram, we do not believe that the 56 Peg primary has a hot corona and transition region. Instead, we propose that the observed X-ray luminosity is due to accretion onto the white dwarf of $\sim 0.1\%$ of the wind from the primary, which we assume has a reasonable mass loss rate of 2×10^{-7} to 4×10^{-9} $M_\odot$ yr^{-1}. The ultraviolet emission lines likely result from reprocessed X-radiation absorbed by the wind. The Mg II K line exhibits a time-varying emission core, that may be explained by ionization of Mg^+ in the wind by X-rays from the white dwarf.

Subject headings: stars: Ba II — stars: individual — stars: late-type — stars: white dwarfs — stars: winds — ultraviolet: spectra

I. INTRODUCTION

Among G and K giants, the barium stars exhibit anomalously strong lines of barium, strontium, and other *s*-process elements (Bidelman and Keenan 1951; Burbidge and Burbidge 1957; Warner 1965). These anomalous abundances have been attributed to slow neutron capture operating in the deep interior of the star, whose nuclear products are then brought to the surface by some unspecified mixing mechanism (Wallerstein and Greenstein 1964) that operates in only a small fraction of the red giants. The carbon and *s*-process surface abundances are of particular interest to the theory of stellar evolution, for they may provide important clues to the evolutionary states of the red giants (Smith, Sneden, and Pilachowski 1980). No theoretical models of core or shell flashes exist that satisfactorily produce the mixing event responsible for the observed abundances (Scalo 1976; Iben 1975). Recently, McClure, Fletcher, and Nemec (1980) found that 10 of 11 barium stars studied are long period binaries, several with 1–2 $M_\odot$ companions. They proposed that the excess abundance of *s*-process elements is the result of mass transfer from the companion star during its evolution to a white dwarf (McClure *et al.*; Smith *et al.*). Subsequently, Böhm-Vitense (1980) published *IUE* short wavelength spectra of the barium star ζ Cap that shows excess continuum flux shortward of 1600 Å, indicative of a hot subluminous companion.

In this paper we present evidence for a white dwarf companion to the mild barium star 56 Peg, analogous to ζ Cap, and discuss the origin of the X-rays and ultraviolet emission-line fluxes. In Table 1 we list the important parameters of the 56 Peg system. Roman (1952) first noted the anomalous strontium and CN strengths, although R. F. Wing and G. L. Lange (1981, private communication) note that the CN band is currently weak. As a mild barium star, luminosity classification is uncertain because the Sr II lines are used as a luminosity criterion (Warren and Williams 1970). An overabundance of Sr may be confused with a more luminous, normal composition supergiant. Both the K0 Ibp (Stebbins and Kron 1956) and K0 IIp (Yoss 1961)

[1] Guest Observer, *IUE Observatory*.
[2] Staff Member, Quantum Physics Division, National Bureau of Standards.

TABLE 1

PHYSICAL PARAMETERS OF 56 PEGASI (K0 IIp + WD) SYSTEM

Parameter	Value	Reference
Adopted distance to 56 Peg	215 pc	1
$R_{56\,\mathrm{Peg}}$	4×10^{12} cm	2
$M_{56\,\mathrm{Peg}}$	5 $M_\odot$	3
R_{WD}	$(2.7 \pm 1.0) \times 10^9$ cm	2
L_x	3×10^{31} ergs s^{-1}	2
m_V	4.7	4
M_V	-1.6	1
$g_{56\,\mathrm{Peg}}$	56 cm s^{-2}; 70 ± 40 cm s^{-2}	3, 5
a (separation)	1–5 $\times 10^{13}$ cm	Estimated
l_x/l_{bol}	6×10^{-6}	2
f_x/f_{visual}	1.4×10^{-4}	2
Q (hardness ratio)	-0.4	2
kT_x (bremsstrahlung fit)	0.45 keV	2
$V \sin i$	≤ 3 km s^{-1}	6

REFERENCES.—(1) Wilson 1976. Previously Eggen 1969 and Wilson and Bappu 1957 have proposed $M_V = -2.2$. (2) This work. (3) Warren and Williams 1970: evolutionary value. (4) Hoffleit 1964. (5) Luck 1977: spectroscopic value. (6) Smith and Dominy 1979.

classifications have been assigned. We prefer luminosity class II for this star on the basis of the Ca II K line absolute magnitude (Wilson 1976) and membership in the Wolf 630 cluster (Eggen 1969). Warren and Williams (1970) and Williams (1975) found an anomalous barium abundance, and suggested that it is a highly evolved 5 $M_\odot$ object. Luck (1977) did not confirm the high barium abundance; however he did confirm the high strontium and lanthanum abundances. The key to understanding the unusual ultraviolet and X-ray emission from this system appears to be the white dwarf companion.

II. OBSERVATIONS

a) Far-UV Continuum and Emission-Line Spectrum

The ultraviolet spectra were obtained with instruments on board the *International Ultraviolet Explorer* satellite (Boggess *et al.* 1978*a*, *b*). Figure 1 shows the low dispersion ultraviolet spectrum of 56 Peg. In addition to the numerous emission lines present, we see an enhanced continuum shortward of 2000 Å, rising to the shorter wavelengths and a broad ($\sim$130 Å) Lyα absorption feature. If there were no interstellar reddening, the far-UV continuum could be matched by a $30{,}000 \pm 2000$ K blackbody curve. The absorption and reddening toward 56 Peg are unknown, but assuming a mean reddening law of $E = \frac{1}{3}A_v = \frac{1}{3}$ (2.0 mag kpc^{-1}) (Allen 1963) and an adopted distance of 215 pc (see Table 1), we estimate $E = 0.11$ mag. Adopting $E = 0.2$ mag as an upper limit, we find that T_{eff} increases to 35,000 K. Thus a reasonable estimate for the dereddened blackbody temperature is $T_{\mathrm{eff}} = 32{,}000 \pm 4000$ K. Assuming $E = 0.1$ mag, the integrated continuum flux from 1250 Å to 1800 Å (7.5×10^{-11} ergs cm^{-2} s^{-1}), and the distance and 32,000 K blackbody temperature imply a radius 2.7×10^9 cm for the hot subluminous companion. If $E = 0.1 \pm 0.1$ mag, then the implied radius is $(2.7 \pm 1.0) \times 10^9$ cm. We compared the observed hot continuum and Lyα absorption feature with a grid of white dwarf model atmosphere calculations of Wesemael *et al.* (1980). Both the $T_{\mathrm{eff}} = 30{,}000$ K, $\log g = 9$ and the $T_{\mathrm{eff}} = 25{,}000$, $\log g = 8$ models fit the observations reasonably well, with $M_{\mathrm{WD}} \sim 1\ M_\odot$.

In Table 2 we list identifications for the observed ultraviolet emission lines, the line fluxes, and the calculated surface fluxes for two possible sources of the emission, the 56 Peg primary and the white dwarf.

b) X-Ray Detection

The object 56 Peg was observed with the *Einstein Observatory* IPC instrument (Giacconi *et al.* 1979) in the 0.15–3.5 keV energy range for about 2 hr on 1980 June 13. The mean count rate was 0.124 ± 0.007 counts s^{-1}. Assuming a 0.5 keV thermal bremsstrahlung spectrum modified by an interstellar hydrogen column density of $N_{\mathrm{H}} = 3 \times 10^{20}$ cm^{-2}, this corresponds to an intrinsic source flux of $\sim 3 \times 10^{-12}$ ergs cm^{-2} s^{-1} (cf. Helfand and Caillault 1982). In addition, a fit to a thermal bremsstrahlung spectrum using the latest, albeit preliminary, IPC instrument parameters gives $kT = 0.45 \pm 0.3$ keV and $N_{\mathrm{H}} = 10^{21.5 \pm 0.5}$. This suggests a higher column density than assumed, which could raise the implied intrinsic flux by a factor of 2. If the X-ray source is embedded in the cool dense stellar wind of the primary star, a still higher column density should be assumed, which would further raise the implied intrinsic flux. The X-ray luminosity assuming $d = 215$ pc and $N_{\mathrm{H}} = 10^{21.5}$ is $\sim 3 \times 10^{31}$ ergs s^{-1}, among the largest L_x for any single star later than B5, and is comparable to the RS CVn binary systems (Walter and Bowyer 1981). The ratio $l_x/l_{\mathrm{bol}} = 6 \times 10^{-6}$, on the other hand, is rather typical for late-type stars with detected soft X-ray emission (Ayres *et al.* 1981; Helfand and Caillault 1982; Pallavicini *et al.* 1981). The large L_x and normal l_x/l_{bol} ratio are consistent because the 56 Peg primary is a bright giant with a large bolometric luminosity due to its large radius. (The ultraviolet luminosity is insignificant compared to the luminosity at longer wavelengths.)

The source showed no significant flux variations on time scales of 2–100 minutes. A Fourier analysis revealed no periodic intensity modulations for periods of 3–3000 s. Zirin (1976) measured an unusually large equivalent width of 1.1 Å for He I λ10830. This is compatible with the measured X-ray emission if the He I 2 ^3S state is populated by recombination following photoionization. Upper limits to radio flux (Bowers and Kundu 1981) and magnetic fields (Brown and Landstreet 1981) have been reported.

c) Ca II K *and* Mg II *k Lines*

The object 56 Peg exhibits an unusual Ca II K line emission profile for its MK spectral type (Linsky *et al.* 1979). The short wavelength emission peak (K_{2V}) is brighter than the long wavelength emission peak (K_{2R}), while most other red giants exhibit a brighter K_{2R} peak, indicative of mass loss (Stencel 1978). The Ca II emission more nearly resembles that seen in solar plages (Shine

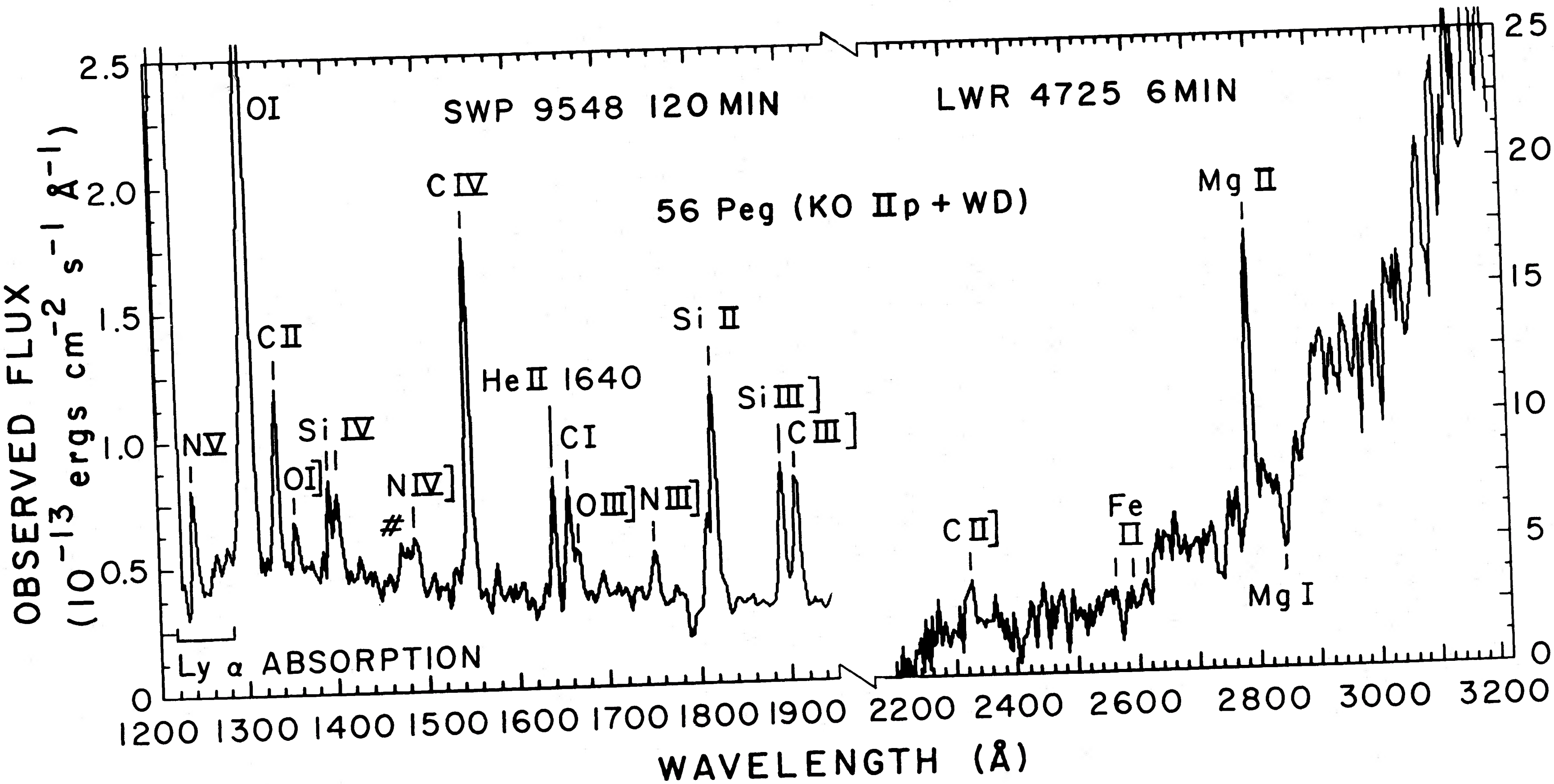

FIG. 1.—Combined *IUE* spectra of 56 Peg (K0 IIp + WD). The data consist of a 120 minute short wavelength exposure (SWP 9548) obtained 1980 July 20 and a 6 minute long wavelength exposure (LWR 4725) obtained 1979 June 8. Note that the observed flux scales differ bv a factor of 10. In the long wavelength region of the spectrum, we see the continuum of the cool primary star ($T_{eff} = 4400$ K), and in the short wavelength region we see a hot continuum from the white dwarf rising to shorter wavelengths. We also see the broad hydrogen Lyman-alpha absorption feature of the white dwarf extending to ~1280 Å. The emission lines are indicated and are likely the result of stellar wind reprocessed X-rays from the white dwarf. The symbol # indicates a particle hit.

TABLE 2

OBSERVED OPTICAL, UV, AND X-RAY FLUXES FROM 56 PEGASI

Species	Observed Flux[a] (ergs cm^2 s^{-1})	Surface Flux[b] 56 Peg	Surface Flux[b] WD	$f/l_{\rm bol}$[c]	Source
			Optical		
Ca II K	1.2(−11)	3.7(+5)	7.2(+11)	2.3(−5)	Linsky *et al.* 1979
Ca II H	1.3(−11)	4.0(+5)	7.8(+11)	2.5(−5)	Linsky *et al.* 1979
			UV		
Mg II *k*	1.9(−11)	5.9(+5)	1.1(+12)	3.7(−5)	This paper LWR 4699 (1979 Jun)
Mg II *h*	1.4(−11)	4.3(+5)	8.4(+11)	2.7(−5)	This paper LWR 4699 (1979 Jun)
Mg II *k*	3.2(−11)	9.9(+5)	1.9(+12)	6.2(−5)	This paper LWR 8324 (1980 Jul)
Mg II *h*	2.6(−11)	8.0(+5)	1.6(+12)	5.0(−5)	This paper LWR 8324 (1980 Jul)
N V 1240 Å	3.0(−13)	9.3(+3)	1.8(+10)	5.8(−7)	This paper LWR 9548 (1980 Jul)
O I 1302 Å	3.8(−12)	1.2(+5)	2.3(+11)	7.3(−6)	This paper LWR 9548 (1980 Jul)
C II 1335 Å	4.6(−13)	1.4(+4)	2.8(+10)	8.8(−6)	This paper LWR 9548 (1980 Jul)
O I? 1356 Å	1.5(−13)	4.7(+4)	9.0(+9)	2.8(−6)	This paper LWR 9548 (1980 Jul)
Si IV 1400 Å	4.7(−13)	1.5(+4)	2.8(+10)	9.0(−7)	This paper LWR 9548 (1980 Jul)
N IV 1485 Å	1:(−13)	3:(+3)	6:(+9)	2:(−7)	This paper LWR 9548 (1980 Jul)
C IV 1549 Å	1.2(−12)	3.7(+4)	7.2(+10)	2.3(−6)	This paper LWR 9548 (1980 Jul)
He II 1640 Å	4.0(−13)	1.2(+4)	2.4(+10)	7.7(−7)	This paper LWR 9548 (1980 Jul)
C I, O III 1660 Å	4.7(−13)	1.5(+4)	2.8(+10)	9.0(−7)	This paper LWR 9548 (1980 Jul)
N III 1749 Å	1.8(−13)	5.6(+3)	1.1(+10)	3.5(−7)	This paper LWR 9548 (1980 Jul)
Si II 1812 Å	9.3(−13)	2.9(+4)	5.6(+10)	1.8(−6)	This paper LWR 9548 (1980 Jul)
Si III 1892 Å	4.9(−13)	1.5(+4)	3.0(+10)	9.4(−7)	This paper LWR 9548 (1980 Jul)
C III 1909 Å	4.8(−13)	1.5(+4)	2.9(+10)	9.2(−7)	This paper LWR 9548 (1980 Jul)
			X-Ray		
0.15–3.5 keV	4(−12)	1.2(+5)	2.4(+11)	6.0(−6)	This paper *Einstein*/IPC (1979 Jun)

[a] Typical uncertainties in *IUE* fluxes for strong lines are 10%–15%.

[b] Surface flux/observed flux = 3.1×10^{16} for the 56 Peg primary using the $V-R$ relation for the stellar diameter given by Linsky *et al.* 1979. The corresponding ratio for the white dwarf is 6.03×10^{22} using $R_{\rm WD} = 2.7 \times 10^9$ cm and $d = 6.63 \times 10^{20}$ cm (215 pc).

[c] $l_{\rm bol} = 5.2 \times 10^{-7}$ ergs cm^2 s^{-1} for the system.

and Linsky 1972). More recent spectra taken in 1979 November by R. E. S. with the KPNO coudé feed, and again in 1980 December by G. S. B. with the Lick 120 inch (3 m) coudé spectrograph, reveal a Ca II K line profile with unchanged asymmetry and intensity.

The Mg II *k* line, on the other hand, shows extreme asymmetry and flux variations (see Fig. 2). Our first observation (1979 June) showed a strongly asymmetric Mg II emission line with the short wavelength peak weaker than the long wavelength peak ($k_{2S} < k_{2L}$). This asymmetry is similar to that typically seen in other K giants (Stencel *et al.* 1980) and indicates expansion of the outer stellar atmosphere in a strong stellar wind. This Mg II asymmetry ($k_{2S} < k_{2L}$) was the opposite of that seen in the Ca II line ($K_{2V} > K_{2R}$) in 1979.

The Mg II *k* line observation of 1980 August showed a complete *reversal* of the Mg *k* line asymmetry, with the shortwave emission peak now brighter ($k_{2S} > k_{2L}$), in agreement with the asymmetry of the Ca II K line. In further observations, taken during 1981, the asymmetry of the Mg *k* line emission core evolved back toward symmetry ($k_{2S} \approx k_{2L}$), consistent with a possible 4 yr modulation. Should future observations lead to the result that the Mg II *k* line profile variations are periodic, then we may presume that this spectral feature is responding to aspect-dependent differences of properties in the binary system.

Further, the Mg II *k* emission base width is anomalously large, implying that the luminosity, computed by the Weiler-Oegerle (1979) Mg II width-luminosity relation, is a factor of 40 larger than that indicated by other luminosity indicators. Differences in luminosity deduced from the Ca II and Mg II line widths are occasionally found among the coronal-type early G supergiants (e.g., β Dra and β Cam), but 56 Peg shows the largest discrepancy detected so far (Basri, Stencel, and Linsky 1981).

III. INTERPRETATION OF THE X-RAY SOURCE

a) *Coronal Source*

Since the launch of the *IUE* and *Einstein Observatories*, the following picture has emerged concerning chromospheres and transition regions in the cool half of the H-R diagram. As one moves off the main sequence and from the yellow giants to the red giants, there occurs a

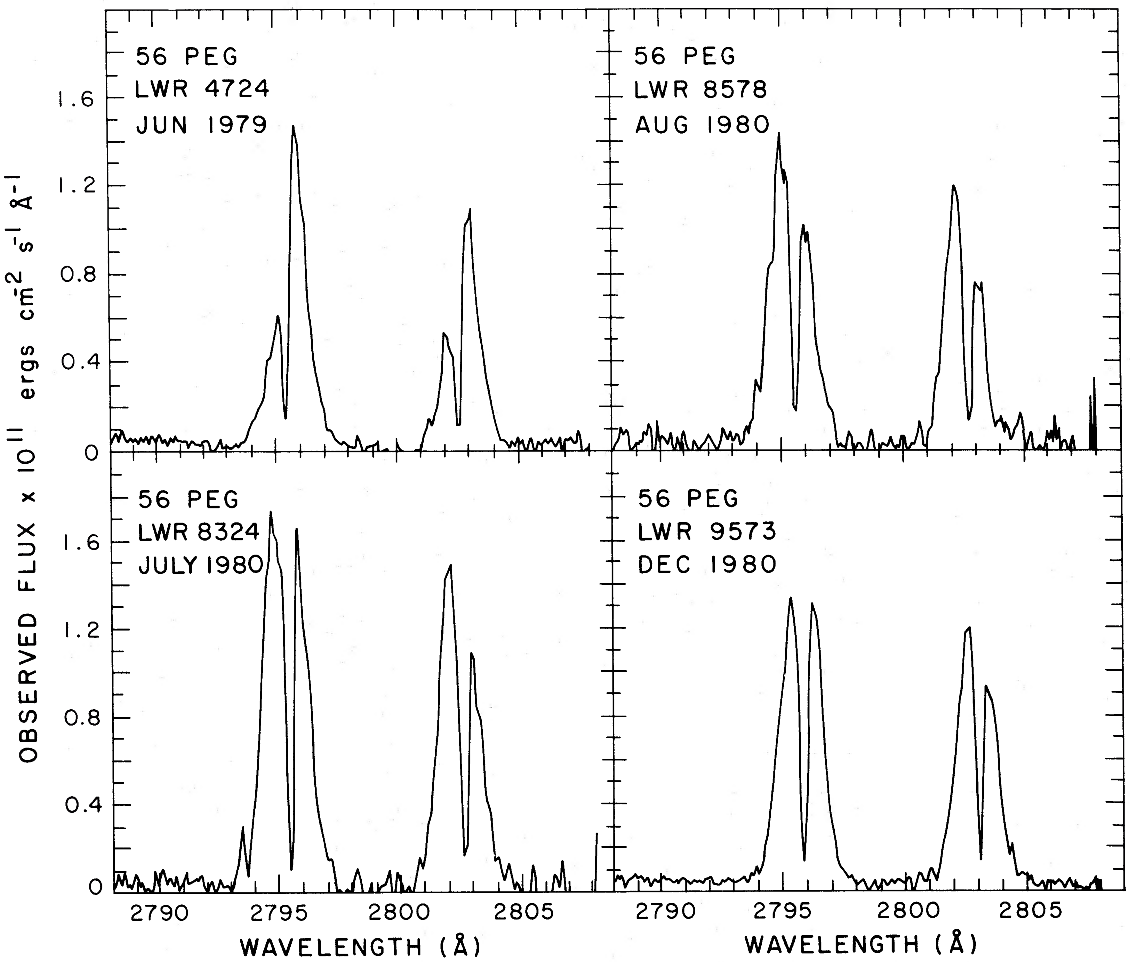

FIG. 2.—Mg II h (2803 Å) and k (2796 Å) line profiles show a dramatic change in the double-peaked emission cores between our first observation in 1979 June and subsequent observations during 1980. The emission core in 1979 was dominated by the long wavelength emission peak, which is likely due to absorption of flux in the short wavelength emission peak by Mg^+ ions in the outflowing wind in front of the star. The profiles in 1980 show a complete reversal of the emission asymmetry to that seen in the Sun and stars without massive winds. Recent 1981 profiles indicate the emission core is now symmetric, perhaps tending toward the asymmetry observed in 1979. This curious change in asymmetry may be explained by X-ray photoionization of Mg^+ in the wind when the white dwarf is in front of the primary star. If this explanation is correct, we expect the photoionized region of the cool stellar wind to rotate with the binary period of the system, giving rise to the time-varying Mg II line profiles. The data suggest a possible 4 year period.

transition near color index $(V-R) = 0.8$ where the soft X-ray and 10^5 K emission disappear, and evidence for large mass loss begins (Ayres *et al.* 1981; Linsky 1981*b*; Simon, Linsky, and Stencel 1982, and references therein; Reimers 1977). However, 56 Peg is exceptional. It has a color index of $(V-R) = 0.97$, but also exhibits *extremely* bright 10^5 K emission and soft X-rays. Our 1979 June observation of the Mg II k line profile suggests substantial outflow of material, but the 1980 observations indicate a reversed, changing profile as previously mentioned.

The current understanding of late-type stars (Vaiana 1980; Linsky 1981*a*, *b*; Pallavicini *et al.* 1981) relates chromospheric and coronal emission to the presence of magnetic fields that are maintained by dynamo action, a process dependent upon stellar rotation and sub-photospheric convection (e.g., Parker 1979). Smith and Dominy (1979), using Fourier transform techniques, showed that 56 Peg is a slow rotator and determined $V \sin i \leq 3$ km s^{-1}. Pallavicini *et al.* (1981) plotted X-ray luminosity against $V \sin i$ for a number of late-type stars. If we place 56 Peg in their Figure 5 (see Schindler *et al.* 1982), we find that it is three and one-half orders of magnitude brighter in X-rays compared to other slowly rotating luminosity class I and II stars in this survey. Hence, 56 Peg clearly violates the rotation-activity correlation, implying that the X-rays are not formed in coronal magnetic flux tubes.

b) *Accretion Source*

Detection of the white dwarf companion makes accretion of wind material from the primary onto the degenerate secondary an important process to consider. The observed luminosity in soft X-rays can be related to the mass accretion rate by: $L_x = \frac{1}{2}\xi G M_s \dot{m}_{\rm acc}/R_s$. This equation assumes that the gravitational potential energy of the captured mass, converted to kinetic energy during free fall, is released upon impact with the star. Half of the X-rays are absorbed by the star, and ξ is that fraction of the produced X-ray spectrum that falls within the soft X-ray pass band. A mass accretion rate of $1 \times 10^{-10}\, M_\odot\, {\rm yr}^{-1}$ would produce the observed X-ray luminosity of 3×10^{31} ergs s^{-1} assuming $\xi \sim 0.1$ (see below).

Is this accretion rate consistent with the dynamics of the binary system? We write the mass accretion rate onto the secondary, $\dot{m}_{\rm acc}$, as the fraction of the cool stellar wind that is gravitationally captured, f_c, times the mass loss rate from the primary, $\dot{M}_p$. The capture fraction is the cross section of the accretion radius divided by the surface area of the sphere with radius equal to the separation. Thus, $\dot{m}_{\rm acc} = f_c \dot{M}_p = (\pi r_a^2/4\pi a^2)\dot{M}_p$. The accretion radius of the white dwarf is defined by equating the kinetic and potential energies of the wind material near the white dwarf; all material within the accretion radius is gravitationally captured. For a mean wind speed relative to the white dwarf, $V_{\rm rel}^2 = V_{\rm wind}^2 + V_{\rm orb}^2$, the accretion radius is $r_a = 2GM_s/V_{\rm rel}^2$. The equations for the observed X-ray luminosity can then be written as

$$L_x = \tfrac{1}{2}\xi G^3 \dot{M}_p a^{-2} V_{\rm rel}^{-4} M_s^3 R_s^{-1}\ {\rm ergs\ s^{-1}}\ .$$

Assuming 100 to 1000 days as the range of periods found for barium star systems (McClure, Fletcher, and Nemec 1980), we find the range of applicable separations for this system is $(1.1–5.3) \times 10^{13}$ cm. Reimers (1977) finds wind speeds of 50–100 km s^{-1} for early K giants. The observed X-ray luminosity of 3×10^{31} ergs s^{-1} then implies a mass loss rate for the primary of $\dot{M}_p = 4 \times 10^{-9}$ to $2 \times 10^{-7}\, M_\odot\, {\rm yr}^{-1}$, reasonable values for this class of stars (e.g., Chiu *et al.* 1977).

Hard X-radiation is produced in the post-shock region where the shock temperature is given by $kT_s = (3/16)\mu m_p v_{\rm freefall}^2 = (3/8)\mu m_p (GM_{\rm WD}/R_{\rm WD})$. For $M_{\rm WD} = 1\, M_\odot$, $R_{\rm WD} = 2.7 \times 10^9$ cm, and a mean particle weight $\mu = 0.6$ (for a fully ionized plasma), this yields $kT_s \sim 15$ keV. The hard X-ray bremsstrahlung emission can be degraded in several ways. Half the emission intercepts the white dwarf surface and is reflected or absorbed. This results in a soft X-ray blackbody spectrum with $T \approx 1.9 \times 10^{-8}(L_x/\Omega)^{1/4}$ eV (see, for example, Fig. 3 in Kylafis and Lamb 1979), where Ω is the solid angle of the flow onto the white dwarf. If the accreting material is sufficiently dense, the electron scattering optical depth exceeds unity, and the hard spectrum may be severely degraded by Compton scattering in the accretion flow. Assuming nonmagnetic steady spherically symmetric accretion, we calculate $\tau_{\rm es} \sim 10^{-5}$ for this flow, which indicates that Compton scattering does not act to degrade the hard X-ray spectrum. Degradation of X-rays will occur in the extended cool dense wind of the primary, by K shell photoionization of the abundant heavy elements; however, this effect is dominant for the soft X-rays, due to the effective photoionization cross section that falls off as energy cubed. (See, for example, calculations of Ross and Fabian 1980.) An accretion disk appears to be the only possible source of opacity great enough to thermalize some fraction of the hard X-ray bremsstrahlung emission in a low accretion system such as this. Clearly, such an accretion disk must form in the binary system in order for the accreting material to lose its angular momentum, but at this time we lack any observational evidence for an accretion disk. The spectra of the known accreting white dwarf systems SS Cyg and U Gem at quiescent times (Fabbiano *et al.* 1981), however, do show soft X-ray luminosities comparable to their hard X-ray luminosities. From *HEAO 1* data J. H. Swank (1981, private communication) derived an upper limit to the hard X-ray flux from 56 Peg, $f_{\rm HX} < 10^{-11}$ cm^{-2} s^{-1}, which is $\sim$2.5 times larger than the soft X-ray flux and thus not very useful. Although we have only an upper limit to the hard X-rays of this system, we believe that accretion of the cool wind onto the white dwarf is the best available explanation for the observed X-ray luminosity, provided the mass loss rate of the primary is typical for its temperature and luminosity as indicated by Mg II observations (§ II*c*). We encourage further calculations of the X-ray spectrum from sources with low accretion rates.

IV. SOURCE OF THE FAR-UV EMISSION-LINE SPECTRUM

In our *IUE* spectra, we observe emission lines of C II, C III, C IV, He II, Si II, Si III, Si IV, N III, and N V, generally associated with the thermal transition regions of stars with hot coronae like the Sun. Since we believe that the 56 Peg primary is unlikely to have a hot corona or a transition region, we explore other possible origins of the far-UV emission-line spectrum.

Calculations of X-ray illuminated stellar atmospheres (London, McCray, and Auer 1981; McCray and Hatchett 1975) show that X-ray heating in X-ray binary systems can induce a corona and a 10^5 K transition region in the atmosphere of the primary directly facing the X-ray source. This mechanism has been used to explain the far-UV emission lines from the HZ Her system (Dupree *et al.* 1978). A quick comparison of the UV line fluxes for 56 Peg with an estimate of the X-ray flux incident on the primary tells us that this mechanism is not feasible, because of the large geometric dilution factor for the X-ray flux. The X-ray flux incident on the primary is estimated to be 8.5×10^2 or 2.0×10^4 ergs cm^{-2} s^{-1} for binary periods of 1000 and 100 days, respectively, a factor of 50 to 2 times *smaller* than the C IV 1550 Å surface flux alone (if from the primary).

We believe that the UV emission lines do not originate in an accretion disk about the white dwarf because the observed lines are narrow. Keplerian orbital velocities about a white dwarf are several thousand kilometers per second, corresponding to a maximum Doppler broadening of $\sim$60 Å at C IV 1550 Å, which is not observed. Since the observed C IV emission is instrumental in width (FWHM $\sim$ 6 Å), we have no evidence for velocities as large as 1000 km s^{-1}. We have recently obtained a high dispersion short wavelength spectrum of 56 Peg with

IUE in its echelle mode. This spectrum will be discussed elsewhere, but the FWHM = 114 km s^{-1} for the C IV 1550 Å line, consistent with the widths of other G and K giants and supergiants (Ayres *et al.* 1982; Stencel *et al.* 1982) but inconsistent with the width expected for an accretion disk. An accretion disk could also produce a power-law continuum in the ultraviolet, but typically such continua are too faint to be seen except where the continua of the hot and cool stars overlap. Our spectra are insufficiently exposed to provide information about an accretion disk continuum, if present. We believe that the observed ultraviolet continuum is thermal emission from the white dwarf and not from an accretion disk because the continuum shape is well fitted by a blackbody and because the stellar Lyα absorption line is clearly present.

The white dwarf atmosphere itself is a possible source of the UV emission. A thermal boundary layer is likely to exist around an accreting white dwarf between the accretion heated region and the photosphere. The opacity of the accretion heated region to radiation from the thermal transition region below depends upon the hydrodynamics of the accretion flow. We performed an isothermal emission measure analysis for several of the UV lines, assuming white dwarf atmospheric densities from Wesemael *et al.* (1980), and found the thickness of the emitting layer to be on the order of 1 km. However, the deduced surface fluxes for the ultraviolet emission lines if formed at the white dwarf (see Table 2) are factors of 10^7 larger than previously found for any other star. This appears highly unlikely, and we cannot accept this explanation.

We propose instead that X-ray illumination of the cool stellar wind from the primary is responsible for the UV emission lines. The X-rays can create a zone of photoionized plasma several giant stellar radii out into the wind, with radius depending upon X-ray energy. We note that the observed X-ray and ultraviolet emission line fluxes are comparable, so that the absorption by the wind of half the initial X-ray flux could explain the energy in all of these ultraviolet emission lines.

This picture may also provide an explanation for the enigmatic Mg II *k* line profile. Magnesium in the cool stellar wind near the X-ray source should be predominantly in Mg^{++} and higher stages of ionization. As a result there may be too little Mg^{+} in the line of sight to produce blueshifted absorption (and thus $k_{2S} > k_{2L}$) when the H II region surrounding the white dwarf is in front of the primary, but sufficient Mg^{+} to produce the absorption at other phases. We would thus expect to see the Mg II *k* line profile exhibit variations with the period of the binary system. In fact, the preliminary data suggest a possible 4 yr period.

V. SUMMARY AND SUGGESTIONS FOR FUTURE WORK

We have presented the *IUE* spectrum and *Einstein* X-ray flux data for the mild barium star 56 Peg that are unusual in several aspects:

1. The *IUE* spectrum clearly shows continuum emission shortward of 2000 Å that rises toward shorter wavelengths. This hot continuum ($T_{\rm eff} = 32{,}000 \pm 4000$ K for reasonable estimates of interstellar reddening) and broad (~ 130 Å) Lyα absorption feature are consistent with emission from a white dwarf companion with $M_{\rm WD} \sim 1\ M_\odot$ and $R_{\rm WD} \sim (2.7 \pm 1.0) \times 10^9$ cm. Our observations, together with those of ζ Cap (Böhm-Vitense 1980) provide support for the hypothesis of McClure, Fletcher, and Nemec (1980) that all barium stars have hot degenerate companions. McClure and colleagues are now monitoring the radial velocity of 56 Peg to determine the orbit of this system.

2. Our *Einstein* observations indicate that this system is very luminous in soft X-rays ($L_x \sim 3 \times 10^{31}$ ergs s^{-1}), contrary to the general trend that cool luminous stars are not detected as X-ray sources. We therefore propose that the soft X-ray detection is not from a corona about the primary star, but is rather due to accretion of a small portion of the cool star wind onto the white dwarf. We find that an accretion rate of $1 \times 10^{-10}\ M_\odot$ yr^{-1} onto the white dwarf is sufficient to explain the observed X-ray luminosity, and that this accretion rate is consistent with a realistic mass loss rate of (4×10^{-9})–$(2 \times 10^{-7})\ M_\odot\ yr^{-1}$ for the primary star and plausible orbital parameters. However, additional calculations of the degredation of hard X-rays in accretion flows for low accretion rates and low opacities ($\tau_{\rm es} \sim 10^{-5}$) are needed to verify our accretion hypothesis.

3. The bright ultraviolet emission-line spectrum, indicative of plasma up to 2×10^5 K, is also unusual for a slowly rotating cool star like the 56 Peg primary. We do not believe that these lines are formed in a transition region around the white dwarf due to the extremely large surface fluxes or in an accretion disk around the white dwarf due to the absence of broad line profiles. Instead, we propose that these lines are formed in an extensive H II region about the white dwarf produced by X-ray photoionization of the wind. If the observed X-rays are only half of those produced, the absorption of the other half by the wind is sufficient to produce the observed ultraviolet emission line flux. Detailed calculations of the emission from X-ray illuminated cool stellar winds are needed to test this hypothesis.

4. The Mg II resonance line profiles may provide a sensitive test of the orbital hypothesis and ionization structure of the cool star wind. We propose that the changing asymmetry of these lines is produced by the absence of Mg^{+} in the line of sight toward the primary star at those times when the H II region around the white dwarf is in front of the primary star. Preliminary data suggest a 4 yr period. We have been monitoring the Mg II line profiles since 1979 June and will report on this program and the SWP high dispersion spectrum in a subsequent publication.

This work was supported in part by National Aeronautics and Space Administration grants NAG5-82 and NGL-06-003-057 through the University of

Colorado. D. J. H. acknowledges support under NASA contract NAS8-30753. We wish to thank Dr. A. Boggess and the staff of the *IUE Observatory* for their assistance in the acquisition and reduction of these data, and Dr. R. McCray for discussions of X-ray illuminated stellar atmospheres and winds.

REFERENCES

Allen, C. W. 1963, *Astrophysical Quantities* (London: Athlone Press), p. 251.
Ayres, T. R., Linsky, J. L., Basri, G. S., Landsman, W., Henry, R. C., Moos, H. W., and Stencel, R. E. 1982, *Ap. J.*, **256**, 550.
Ayres, T. R., Linsky, J. L., Vaiana, G. S., Golub, L., and Rosner, R. 1981, *Ap. J.*, **250**, 293.
Basri, G., Stencel, R., and Linsky, J. L. 1980, *Bull. A.A.S.*, **12**, 805.
Bidelman, W. P., and Keenan, P. C. 1951, *Ap. J.*, **114**, 473.
Boggess, A., *et al.* 1978*a*, *Nature*, **275**, 372.
———. 1978*b*, *Nature*, **275**, 377.
Böhm-Vitense, E. 1980, *Ap. J.* (*Letters*), **239**, L79.
Bowers, P. F., and Kundu, M. R. 1981, *A.J.*, **86**, 569.
Brown, D. N., and Landstreet, J. D. 1981, *Ap. J.*, **246**, 899.
Burbidge, E. M., and Burbidge, G. R. 1957, *Ap. J.*, **126**, 357.
Chiu, H. Y., Adams, P. S., Linsky, J. L., Basri, G. S., Maran, S. P., and Hobbs, R. W. 1977, *Ap. J.*, **211**, 453.
Dupree, A. K., *et al.* 1978, *Nature*, **275**, 400.
Eggen, O. 1969, *Pub. A.S.P.*, **81**, 553.
Fabbiano, G., Hartmann, L., Raymond, J., Steiner, J., Branduardi-Raymont, G., and Matilsky, T. 1981, *Ap. J.*, **243**, 911.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Helfand, D., and Caillault, J. P. 1982, *Ap. J.*, **253**, 760.
Hoffleit, D. 1964, *Catalogue of Bright Stars* (New Haven: Yale University Observatory).
Iben, I. 1975, *Ap. J.*, **196**, 525.
Kylafis, N. D., and Lamb, D. Q. 1979, *Ap. J.* (*Letters*), **228**, L105.
Linsky, J. L. 1981*a*, in *X-Ray Astronomy with the Einstein Satellite*, ed. R. Giacconi (Dordrecht: Reidel), p. 19.
———. 1981*b*, in *Solar Phenomena in Stars and Stellar Systems*, ed. R. M. Bonnet and A. K. Dupree (Dordrecht: Reidel), p. 99.
Linsky, J. L., Worden, S., McClintock, W., and Robertson, R. 1979, *Ap. J. Suppl.*, **41**, 47.
London, R., McCray, R., and Auer, L. H. 1981, *Ap. J.*, **243**, 970.
Luck, R. E. 1977, *Ap. J.*, **212**, 743.
McClure, R. D., Fletcher, J. M., and Nemec, J. M. 1980, *Ap. J.* (*Letters*), **238**, L35.
McCray, R., and Hatchett, S. 1975, *Ap. J.*, **199**, 196.
Pallavicini, R., Golub, L., Rosner, R., Vaiana, G. S., Ayres, T. R., and Linsky, J. L. 1981, *Ap. J.*, **248**, 279.
Parker, E. N. 1979, *Cosmical Magnetic Fields* (Oxford: Clarendon Press).
Reimers, D. 1977, *Astr. Ap.*, **57**, 395.
Roman, N. G. 1952, *Ap. J.*, **116**, 122.
Ross, R. R., and Fabian, A. C. 1980, *M.N.R.A.S.*, **193**, 1P.
Scalo, J. M. 1976, *Ap. J.*, **206**, 474.
Schindler, M., Stencel, R. E., Linsky, J. L., Basri, G. S., and Helfand, D. 1982, in *Proc. Second Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, ed. M. S. Giampapa and L. Golub, *Smithsonian Ap. Obs. Spec. Rept., No. 392*, Vol. **2**, p. 125.
Shine, R., and Linsky, J. L. 1972, *Solar Phys.*, **25**, 357.
Simon, T., Linsky, J. L., and Stencel, R. E. 1982, *Ap. J.*, **257**, 225.
Smith, M. A., and Dominy, J. F. 1979, *Ap. J.*, **231**, 477.
Smith, V. V., Sneden, C., and Pilachowski, C. A. 1980, *Pub. A.S.P.*, **92**, 809.
Stebbins, J., and Kron, G. 1956, *Ap. J.*, **123**, 440.
Stencel, R. E. 1978, *Ap. J.* (*Letters*), **233**, L37.
Stencel, R. E., Linsky, J. L., Ayres, T. R., Jordan, C., and Brown, A. 1982, *Ap. J.*, submitted.
Stencel, R. E., Mullan, D., Linsky, J. L., Basri, G. S., and Worden, S. 1980, *Ap. J. Suppl.*, **44**, 383.
Vaiana, G. S. 1980, in *Cool Stars, Stellar Systems, and the Sun*, ed. A. K. Dupree, *Smithsonian Ap. Obs. Spec. Rept., No. 389*, p. 195.
Wallerstein, G., and Greenstein, J. L. 1964, *Ap. J.*, **139**, 1163.
Walter, F., and Bowyer, S. 1981, *Ap. J.*, **245**, 671.
Warner, B. 1965, *M.N.R.A.S.*, **129**, 263.
Warren, P. R., and Williams, P. M. 1970, *Observatory*, **90**, 115.
Weiler, E., and Oegerle, W. 1979, *Ap. J. Suppl.*, **39**, 537.
Wesemael, F., Auer, L. H., Van Horn, H. M., and Savedoff, M. P. 1980, *Ap. J. Suppl.*, **43**, 159.
Williams, P. M. 1975, *M.N.R.A.S.*, **170**, 343.
Wilson, O. 1976, *Ap. J.*, **205**, 823.
Wilson, O., and Bappu, V. 1957, *Ap. J.*, **125**, 661.
Yoss, K. M. 1961, *Ap. J.*, **134**, 809.
Zirin, H. 1976, *Ap. J.*, **208**, 414.

G. S. Basri: University of California Space Sciences Laboratory, Grizzly Peak Boulevard, Berkeley, CA 94720

D. J. Helfand: Columbia Astrophysical Laboratory, Columbia University, New York, NY 10027

J. L. Linsky: Joint Institute for Laboratory Astrophysics, Mail Code 440, University of Colorado, Boulder, CO 80309

M. Schindler: Box 60, West Hartford, VT 05084

R. E. Stencel: Code EZ-7, NASA Headquarters, Washington, DC 20546