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First far–UV observations of KQ Puppis with FUSE⋆

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Abstract. We report the first far–ultraviolet spectrum of the emission line spectroscopic binary KQ Pup (M2Iab+B0Ve), obtained with FUSE shortly after conjunction at orbital phase $\Phi = 0.13$. The spectrum presents a sharp flux cutoff at 1040 Å; longwards, it is dominated by a large amount of resonant and low excitation transitions of neutral and singly ionized species, probably mostly of circumsystem origin, and by the Lyman absorption bands of H_2, whose strength corresponds to an interstellar H_2 column density of $\sim 2 \times 10^{20}$ cm^{-2}, indicating a fraction of molecular hydrogen $2N(H_2)/[N(\text{H}\,\textsc{i})+2N(H_2)]$ of ∼0.4. An $N(\text{H}\,\textsc{i})/E_{B-V}$ ratio of 4.3×10^{21} is derived from the IUE spectra. The long–term UV monitoring of KQ Pup with IUE, HST and FUSE reveals a large decrease of the far–UV flux since orbital phase 0.82 and occupying more than 0.3 of the orbital period. This "shell" episode is attributed to line absorption and to Lyα Rayleigh scattering due to an extended dense cool envelope in the line of sight of the B star.

Key words. stars: binaries: spectroscopic – stars: individual: KQ Pup – stars: mass-loss – ultraviolet: stars

1. Introduction

KQ Pup is a spectroscopic, non–eclipsing, binary system of the VV Cephei–type displaying in the optical and ultraviolet a rich emission line spectrum mostly formed in the M supergiant wind ionized by the UV photons of the hot companion.

The exact nature of the hot star is not well known yet. Rossi et al. (1992) show that the slope of the UV continuum measured near quadrature in the International Ultraviolet Explorer (IUE) spectra indicates an effective temperature of $T_{\rm eff} \geq 30\,000$ K, and that the He I 3819 Å line suggests a spectral type B0–2 V. The presence of non–resonance lines of Si III, Ti III, Fe III, etc. in the IUE spectra might suggest an earlier spectral type. However, the highly positive radial velocity of these lines and the time variability of their profile with orbital phase (Rossi et al. 1998) seem to indicate that their origin could be mostly non–photospheric, possibly formed in ionized matter streaming towards the hot star.

The optical and ultraviolet spectra have shown deep variations along its 26 year period that are mostly associated with the high orbital eccentricity (0.46) and with diffuse matter irregularly distributed all around the system.

Recently, González–Riestra et al. (2002) re–analyzed all the available optical radial velocity data, and derived a new period for the system of 9500 ± 50 d, implying that the last periastron passage occurred around JD 2450811 (December 28, 1997), and the conjunction, with the B star behind the M star, around November 2, 1999. (It must be remembered that this system does not undergo optical eclipses.) In the following we shall use these new ephemerides.

The ultraviolet spectrum of KQ Pup had been observed with HST–STIS on October 7, 1999 (P.I. P. D. Bennett; Bauer et al. 2001). These observations, intended to be made near periastron, were actually performed at orbital phase 0.07, just one month before conjunction.

Our Far Ultraviolet Spectroscopic Explorer (FUSE) observations were made near conjunction (M supergiant in front of the B star). The purpose was to investigate the nature of the hot component, as well as to see the signature of a possible eclipse by the M–star envelope, or by its inner wind. Because of the mentioned above reanalysis of the radial velocity curve, the FUSE observations were actually done after the conjunction, at phase 0.13 when, as we shall show, the B star was slowly emerging from a long–lasting shell episode.

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⋆ Based on observations made with the NASA-CNES-CSA Far Ultraviolet Spectroscopic Explorer. FUSE is operated for NASA by the Johns Hopkins University under NASA contract NAS5-32985. The HST spectrum used in this paper was obtained from the Multimission Archive at the Space Telescope Science Institute (MAST).

Table 1. Mean radial velocity of absorption lines of different species in the FUSE spectrum of KQ Puppis.

species	n^a	$v_{\rm rad}{}^b$
$H_2{}^c$	15	32.8 ± 5.9
C I	43	51.3 ± 23.4
N I	3	47.0 ± 5.3
P II	5	36.6 ± 1.6
Cl I	19	38.7 ± 25.5
Cl II	3	68.6 ± 18.8
Mn II	3	55.1 ± 8.4
Cr II	11	34.4 ± 19.2
Fe II	72	40.1 ± 14.8

Notes to the table: [a] number of lines; [b] heliocentric radial velocities (km s^{-1}); [c] Lyman bands.

Section 2 presents the FUSE observations of KQ Pup. In Sect. 3 the study focuses on the analysis of the energy distribution and absorption line spectrum, based on the comparison with a template reddened B–type spectrum. The analysis of the long term variation in Sect. 4 has been performed combining data from different satellites. The results are discussed in Sect. 5.

2. FUSE observations

Far–ultraviolet ($\lambda\lambda$ 907–1188 Å) spectroscopic observations of KQ Puppis were obtained with FUSE (Far Ultraviolet Satellite Explorer) on April 5, 2001, at phase 0.13, according to the ephemeris derived by González-Riestra et al. (2002).

The observations were performed in HIST mode, with the large aperture (LWRS, 30 × 30 arcsec). Four 682 s exposures were taken, with a total exposure time of 2 728 s. The first exposure was taken during spacecraft day, and the last two during night.

Data were processed using the CALFUSE standard reduction pipeline (version 1.8.7). Spectra from different exposures and detectors were combined following the guidelines given in the "FUSE Data Analysis Cookbook".

It has been found that in CALFUSE 1.8.7 and earlier versions, the heliocentric velocity correction had been applied with the wrong sign. We have corrected our spectrum for this error, by applying the heliocentric velocity correction (+23.5 km s^{-1} in this case) twice in the opposite direction.

3. Spectral analysis

The FUSE calibrated spectrum of KQ Pup is shown in Fig. 1. The spectrum is characterized by a sharp cut–off near ~1040 Å, with a very low flux level shortwards. At longer wavelengths the spectrum is characterized by deep, broad absorptions due to interstellar Lyman H_2 bands, and by a large number (~3×10^2) of narrow absorption lines. There are also a few emission lines that can be ascribed to daylight airglow and geocoronal emissions, that have been easily identified by comparing exposures taken with the satellite inside and outside the Earth shadow.

3.1. Line identification

Molecular hydrogen lines have been identified using the wavelength tables given by Morton & Dinerstein (1976). The strongest lines of each band are saturated (see Figs. 1 and 2). Therefore we have measured only the wavelength of the faintest narrower components, and derived a mean radial velocity of 32.8 km s^{-1}, close to the system velocity of 34.4 km s^{-1} (Cowley 1965). However, this could well be a chance coincidence, since the accuracy of the zero point of the FUSE wavelength scale is limited by the centering of the star in the spectrograph aperture and by thermally–induced rotations of the gratings. Zero point errors can be as large as ±0.25 Å (about ±70 km s^{-1} at 1100 Å).

In principle, the H_2 velocity measurement could be used to set the zero point of the FUSE wavelength scale, by comparison with the velocity of the interstellar lines seen in other spectral regions. However, the most promising resonance optical lines (e.g. the Ca II K–line) have a complex structure, which so far prevented the accurate measurement of the velocity of the interstellar component (Altamore et al. 1992). Also, in our preliminary analysis of the IUE high resolution spectra we have been unable to separate clearly the interstellar lines from the absorption components formed in the KQ Pup environment, due to the complex and variable profile of the low ionization lines.New very high resolution optical spectra are planned in order to set the radial velocity scale of the interstellar system.

Apart from the H_2 features, there is a large number of narrow lines that can be identified with resonance and low excitation transitions of several neutral and ionized species.

Since most of the lines are blended, we have measured the position of only a total of 180 isolated lines between 1040 and 1180 Å. Out of them we have identified 72 Fe II resonance and low–excitation lines with a mean radial velocity of 40.1 km s^{-1}. Table 1 summarises the mean radial velocity of different absorption species. The fairly large errors of some species have to be attributed to unresolved blends of different atomic lines. The radial velocity of the lower temperature atomic species appears systematically more positive with respect to that of molecular hydrogen, and seems to suggest a local (=circumsystem) rather than interstellar origin. But a significant interstellar contribution cannot be disregarded. As discussed below, the circumsystem component is expected to be largely variable in strength. Therefore, the best way to separate it from the interstellar one would be new FUSE observations at phases later than ~0.25.

One stellar feature that can be unambiguously identified is the C III sextet at 1176 Å, with a *FWHM* of approximately 4.3–4.7 Å. The FUSE spectrum also shows other lines, such as N II and Fe III (see Fig. 1), which could be attributed to the B–star spectrum. These lines are in fact present in the photospheric spectrum of the B2e star HR 5223 (Frémat et al. 2002). However, the large variability with orbital phase of the lines of the doubly ionized species observed with IUE (Rossi et al. 1998) suggests that these lines may largely be non photospheric. Also in this case, new FUSE observations at a different phase should help clarify the problem.

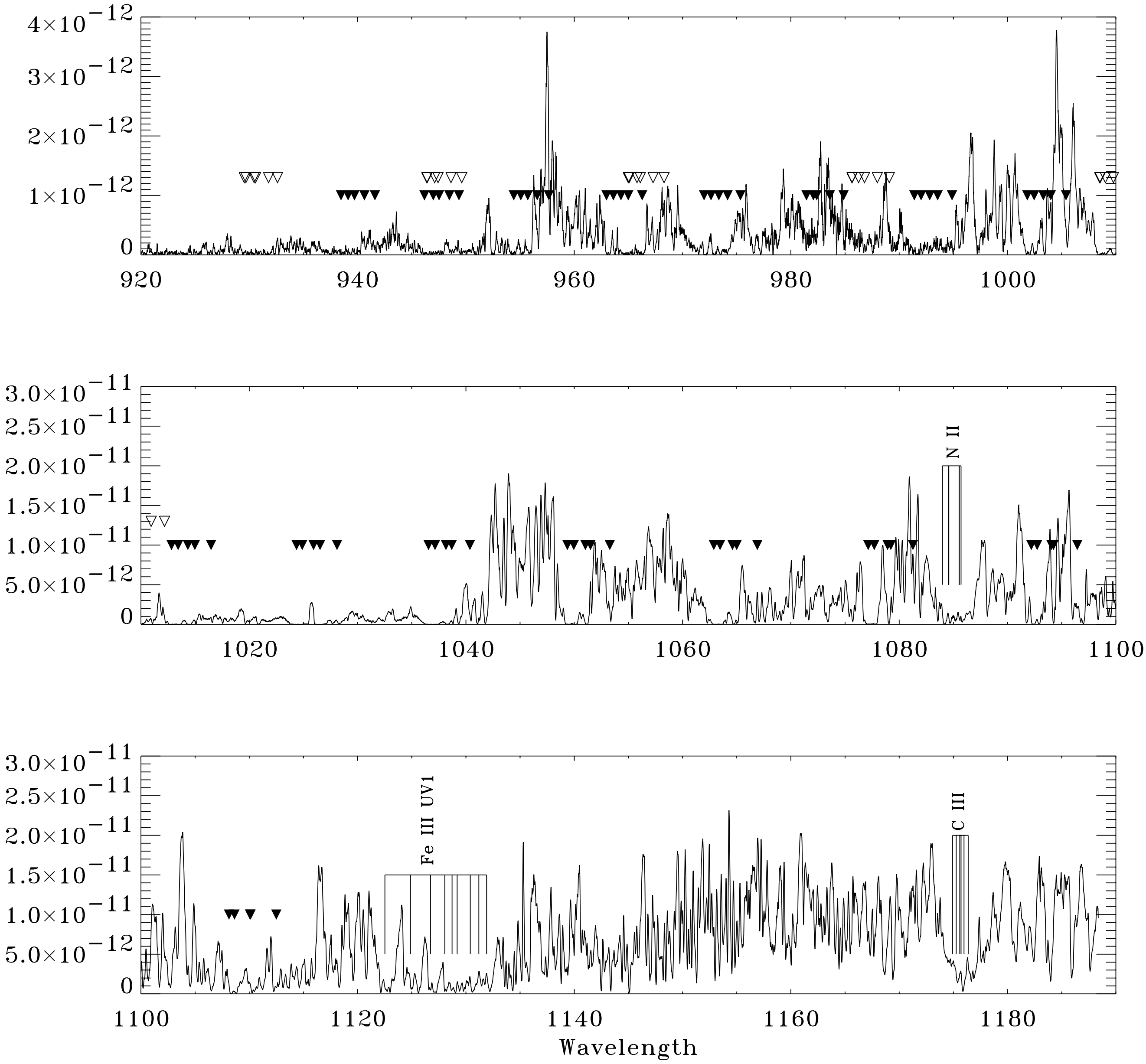

Fig. 1. The FUSE far–ultraviolet spectrum of KQ Pup. Note the different scale of the upper panel, and the flux cut–off near 1040 Å. Clearly visible is the broad C III photospheric absorption at 1176 Å. Other possible photospheric lines are identified. The main interstellar H_2 features are marked with triangles (open symbols: Werner bands, filled symbols: Lyman bands). Flux units are erg cm^{-2} s^{-1} $Å^{-1}$.

Finally, there is no evidence for emission lines, as seen in the optical–UV, apart from the airglow and geocoronal lines mentioned above.

3.2. Interstellar absorption

From the depth of the 2200 Å band observed with IUE, Rossi et al. (1992) derived an interstellar extinction in the direction of KQ Pup of $E_{B-V} = 0.14$. We have derived the H I column density from the width of the red wing of Lyman α using the best exposed IUE high resolution spectrum far from the "shell" phase (see Sect. 4). The measured $FWHM$ of $W_{Ly\alpha}$, 12.2 ± 0.6 Å, corresponds, from the relation $N(\mathrm{H\,I}) = 4.068 \times 10^{18}\ W_{Ly\alpha}{}^2$, to $N(\mathrm{H\,I}) = (6.0 \pm 0.6) \times 10^{20}$ cm^{-2}. Comparing with the E_{B-V} given above, we obtain an $N(\mathrm{H\,I})/E_{B-V}$ ratio of 4.3×10^{21}, in good agreement with the mean ratio found by Shull & van Steenberg (1985) for stars with distances between 1 and 2 kpc (Rossi et al. 1992 derived a distance of 1.4 ± 0.2 kpc for KQ Pup).

A detailed analysis of the interstellar spectrum is beyond the scope of this paper, but in order to evaluate the molecular hydrogen column density, we have compared the observed spectrum with the model atmospheres provided in the FUSE spectral simulator using different values of the interstellar molecular hydrogen column density $N(H_2)$. Models with effective temperatures close to that derived by Rossi et al. (1992) for the early–type component of the KQ Pup system largely deviate from the observed far–UV spectrum. However, the IUE

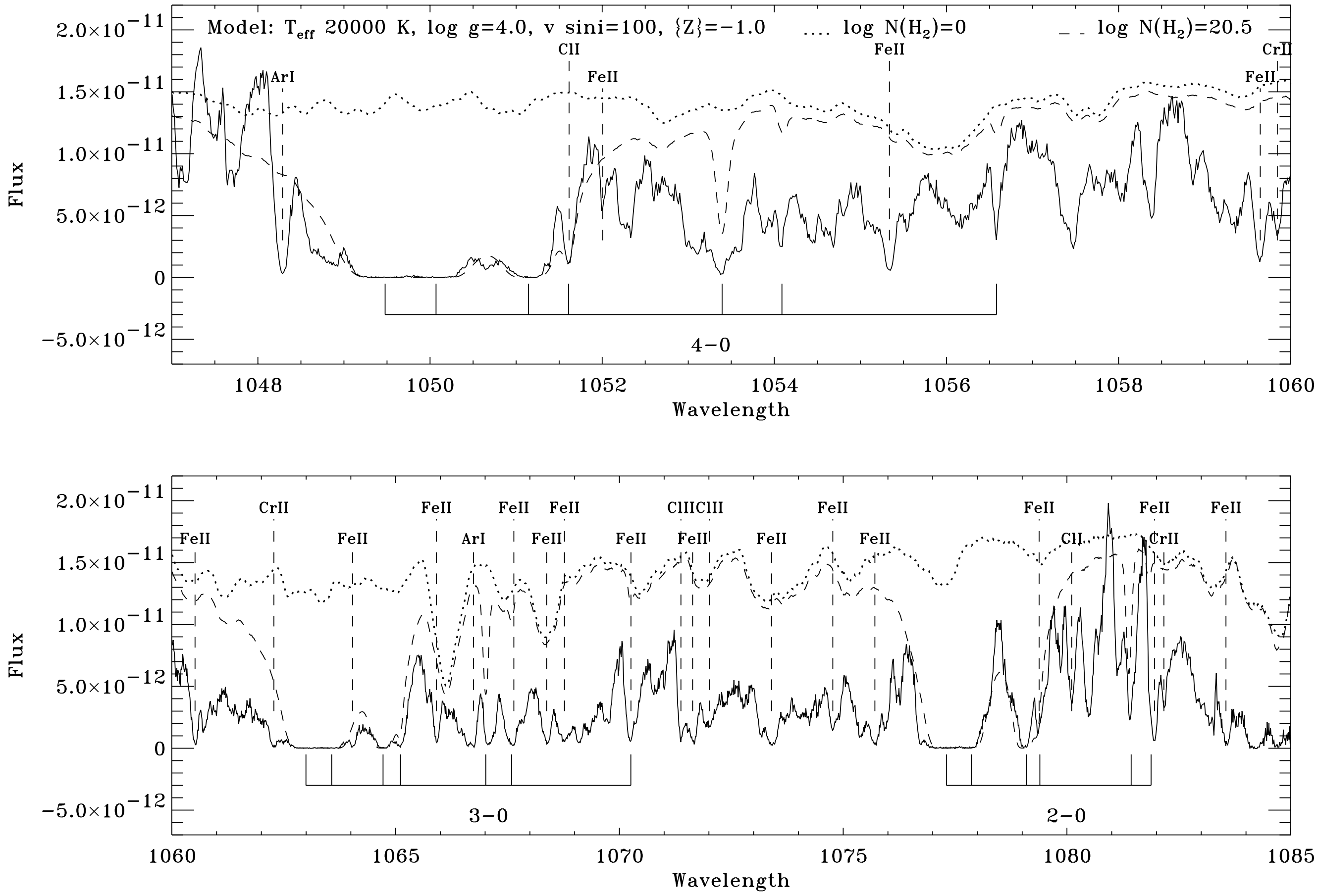

Fig. 2. The FUSE spectrum of KQ Pup in the spectral region 1050–1090 Å, showing the 2–0, 3–0 and 4–0 Lyman bands of interstellar H_2. The observed spectrum is compared to a theoretical model atmosphere (see text for details) and to the same model with a column density of interstellar H_2 of 3×10^{20} cm^{-2}. Some atomic transitions are also indicated. Flux units are as in Fig. 1.

observations have marked since phase 0.82 the presence of an intense absorption spectrum of circumstellar origin which increased towards shorter wavelengths (see Fig. 3). We therefore expect a strong contribution of the circumstellar absorption at the time of the FUSE observations that should largely affect the far–UV energy distribution.

For comparison we have adopted a model atmosphere with $T = 20\,000$ K, $\log g = 4.0$, and $[Z] = -1$ (dotted line in Fig. 2), with different interstellar H_2 column densities. In spite of having adopted a temperature lower than that derived by Rossi et al. (1992) from the IUE spectrum, the absorbed model still largely deviates from the observed spectrum, which has to be explained by the presence at the time of FUSE observations of a large number of unresolved non–photospheric narrow absorption lines, as mentioned above.

The observed strength of the unsaturated H_2 lines and the width of the damping wings of the strongest lines in the spectrum of KQ Pup appear intermediate between the models for $\log N(H_2) = 20.0$ and 20.5, providing a best estimate value of 20.3 ± 0.2 for the logarithm of the total H_2 column density (essentially of the $J = 0$ and 1 terms). The interstellar fraction of molecular hydrogen, $f = 2N(H_2)/[N(\mathrm{HI}) + 2N(H_2)]$, turns out to be 0.4.

4. Long term spectral variation

The ultraviolet spectrum of KQ Pup was monitored by the International Ultraviolet Explorer (IUE) from April 1978 to November 1995, covering the 0.24–0.92 phase interval of the orbital motion. This period of time was marked by dramatic spectral variations described by Rossi et al. (1998). In particular, they found since May 1993 ($\Phi = 0.82$) a general broadening of the absorption lines, due to the appearance of a new, red-shifted, absorption component. This phase was characterized by a general increase of the absorption line spectrum, a large decrease of the far–UV continuum and a large broadening of Lyα. This "shell" phase was deeper at the time of the HST observations at phase 0.07, and slightly recovered during the FUSE observations. Figure 3 illustrates the far–UV spectral variation of KQ Pup during the shell phase.

To better show the large wavelength dependence of the changes, we have measured the continuum level in five different spectral regions – two of which are common to the three experiments – that are less affected by the spectral lines: 1166–1167 Å, 1186–1187 Å, 1224–1225 Å, 1313–1314 Å, and 1453–1454 Å. The results are shown in Fig. 4. It is evident in the figure that the decrease of the far–UV continuum started between $\Phi = 0.81$ and 0.82, and that it reached a deep minimum

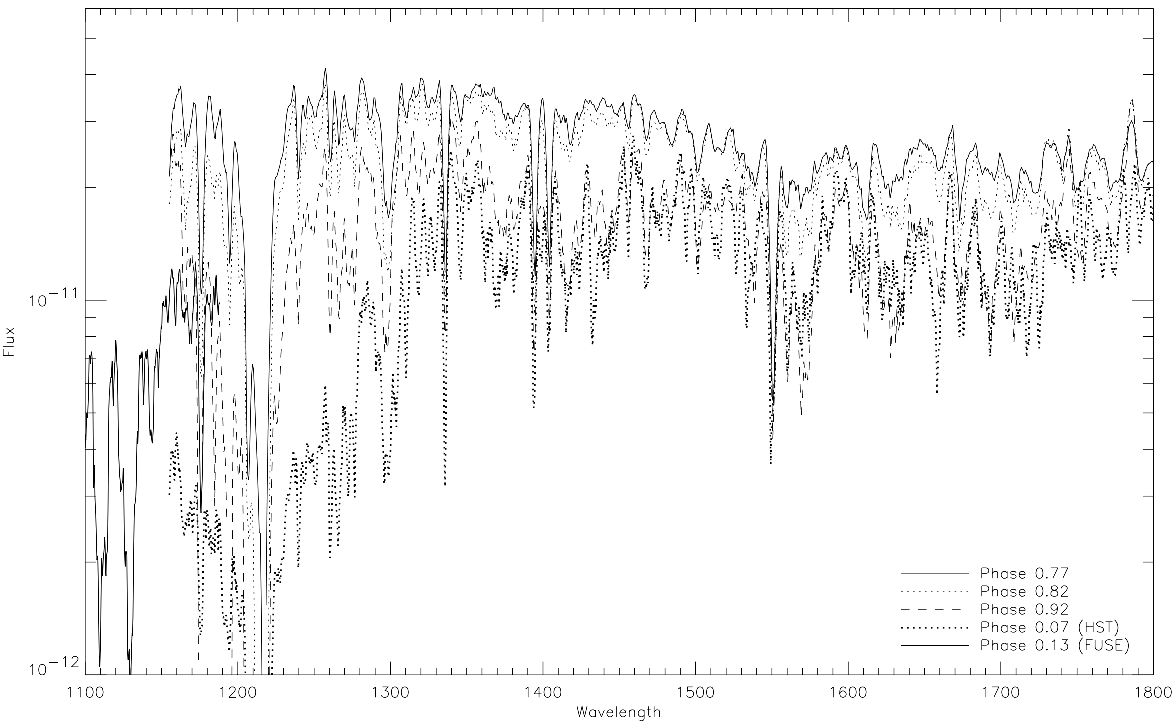

Fig. 3. Spectral variation of KQ Pup in the far–UV during the period 1993–2001, based on IUE, FUSE, and HST observations. The top three spectra are binned high resolution IUE spectra. Flux units are as in Fig. 1.

at time of, or most probably before, the HST observations of October 1999. The flux decrease was minimum at 1453 Å, and vanished longward of 1500 Å (see also González–Riestra et al. 2002). A slight recovering of the flux near Lyα was detected in our FUSE observations.

5. Discussion

We have found that in April 2001 the far–UV energy distribution of KQ Pup was about 2–3 times lower than foreseen on the basis of the extrapolation of the average IUE energy distribution from phase 0.2 to 0.8. It has been shown that this decrease has to be associated with the long term spectral variability of the object, which, according to the HST and FUSE observations, should have reached a minimum around the times of periastron passage and of inferior conjunction.

The decrease of the continuum in the far–UV cannot be ascribed to eclipse of the hot component of the system, since no change was seen longward of 1500 Å (González–Riestra et al. 2002) where, as shown by Rossi et al. (1992), the hot star continuum still dominates the UV spectrum. In addition, the duration of the minimum was much longer than that expected from the stellar sizes. Therefore, the minimum should be attributed to occultation by extended opaque matter partly surrounding the B star, that also produced a deep "shell" absorption spectrum. Our observations show that this matter is present in front of the B star from phase 0.82 to later than phase 0.13, with a sharp edge at the beginning and a gradual opacity increase. The shell phase should have in total lasted more than three tenths of the orbital cycle.

The observed UV continuum decrease, and its wavelength dependence, can be explained at least partly by *Rayleigh scattering* in the wind of the cool supergiant of the hot star's radiation by neutral hydrogen in the Lyα line, as it was observed in other binary systems, such as RW Hya, SY Mus and BF Cyg (Dumm et al. 2000; Pereira et al. 1995; González-Riestra et al. 1990). The fact that the flux decrease started near the superior conjunction, with the B star closer to the observer, means that the scattering neutral material is placed on the opposite side with respect to the M star. Most probably, the cool star wind when passes close to the B star is bended by the orbital motion, thus forming a wide and dense stream. Indeed, similar structures have been hypothesized to explain some UV peculiarities of the ζ Aur stars (e.g. Ahmad 1986; Chapman 1981), and are taken as an indication of the presence accretion columns onto the hot companions. It would be interesting to investigate whether this effect in KQ Pup is associated with the redshift of the doubly ionized absorption lines observed by Rossi et al. (1998).

The FUSE spectrum of KQ Pup also presents a sharp cut–off near ~1040 Å, which indicates a strong opacity increase at this wavelength. This effect is not seen in the FUSE spectrum of the B2e star HR 5223 (Frémat et al. 2002), but it is present in intermediate and late–type B–supergiants observed with COPERNICUS (Walborn & Bohlin 1996), as well as in the ORPHEUS spectra of the Algol binary systems described by Peters & Polidan (1998). In KQ Pup this feature can be associated with the shell phase, and could be identified with the ionization limit of Ca^+ at 1044 Å, and with Rayleigh scattering in Lyβ. Clearly, this feature is not inherent to the B–star spectrum, and we expect it to largely vanish when the shell event ends.

The narrow resonance and low–excitation lines of neutral and singly ionized species observed in the FUSE spectrum

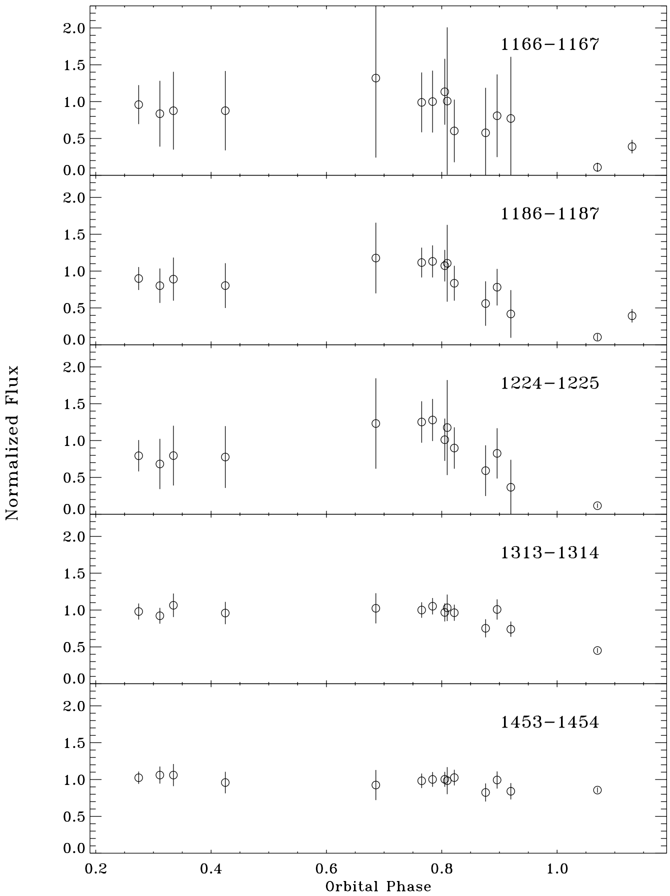

Fig. 4. Long–term flux variation of the far–UV spectrum of KQ Pup in five selected regions free of strong absorption lines, based on observations made with IUE (phases 0.27 to 0.92), HST–STIS (phase 1.07), and FUSE (phase 1.13). Flux is normalized to the average from phases 0.2 to 0.8.

should have in part the same origin of the variable low temperature lines observed in the IUE spectra during the shell event. Hence, they should be largely formed in the circumsystem medium filled in by the M–star wind, in accordance with what has been observed in the short wavelength IUE range (Muratorio et al. 1992; Rossi et al. 1992). They can also be partly of interstellar origin, but at the moment, with only one FUSE spectrum taken during a deep shell phase, we are unable to separate interstellar from circumsystem lines.

Little can be said at the moment about the far–UV energy distribution and spectrum of the hot component of the KQ Pup system. As for the higher ionization absorption lines, Rossi et al. (1992) suggested that they could be formed in a shock near the hot star due to collision of the M and B star winds. Dynamical instabilities near the shock might produce clouds that are heated and eventually accreted by the hot star. This leaves open the question of which lines are formed in the B–star photosphere, and what is its effective temperature.

A thorough analysis of the high resolution ultraviolet spectra of KQ Pup before and during the shell phase is in progress in order to investigate the line profile variation, and to reveal the origin of the low and high ionization lines.

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