

# Optical and Infrared Observations of Two Interesting Short Period Binaries: Tau 4 & SDSS J1212

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## ABSTRACT

We present new optical photometric and spectroscopic observations and K-band spectroscopy of two interesting short-period binaries: Tau 4 and SDSS J121209.31+013627.7. Tau 4 shows highly modulated optical light but no periodic trends are detected. K-band spectroscopy shows H and He emission and a fairly typical low mass star continuum. We detect no evidence for cyclotron emission in the K-band as was previously suggested. The orbital period and nature of Tau 4 (dwarf novae or magnetic) remain a mystery. Optical spectroscopy of J1212 shows Zeeman split Balmer lines but no  $i$  H $\alpha$  emission as previously reported. Their cause was thought to be irradiation but evidence here clearly rules this out. The pre-polar nature of J1212 is called into question and we relate the binary to its near twin, EF Eri.

*Subject headings:* binaries: close – stars: stars: general — stars: individual (Tau 4, SDSS J1212)

## 1. Introduction

Cataclysmic variables are semi-detached binaries in which a white dwarf primary is accreting material from its close neighbor, a low-mass Roche-lobe filling object. The donor stars are often taken to be of the main sequence variety, but observational evidence often suggests that they are more evolved. The generally accepted present-day paradigm for CV evolution (Howell et al., 2001) can not account for the low carbon abundance observed or for a different evolution for magnetic CVs vs. non-magnetic CVs.

Short period binaries with white dwarf primaries and substellar companions are likely to be related to CVs and are useful to help us understand the evolution of systems into or out of the interacting stage. Tau 4 and J1212 are interesting examples of short period (or likely short period) binaries for which their exact nature and evolutionary status are unknown. Tau 4 has been suggested to be a magnetic Cv while J1212 was thought to be a detached binary soon to become a polar.

## 2. Observations and Reductions

### 2.1. Infrared Spectroscopy

All the infrared spectra presented herein were obtained at the Keck II telescope on Mauna Kea, Hawaii. The spectra were obtained on 4 and 5 March 2007 UT using the NIRSPEC. NIRSPEC was used in low resolution mode with the slit width set to  $0.38''$  as we had seeing near  $0.4''$  on both nights. We chose a grating tilt to cover the K band spectral range of 2.04-2.40 micron with a dispersion of  $4.27 \text{ \AA}/\text{pixel}$  or a velocity resolution near 110 km/sec. All stars were observed using a standard ABBA nod pattern on the slit and the four nod exposures were usually combined into single final spectra due to the limited S/N per nod. Observations of bright A stars nearby in time and location were used for telluric

correction. The Keck spectra were reduced using the IDL routine REDSPEC especially developed for NIRSPEC reductions. A stars are nearly featureless in the K band except for Brackett $\gamma$  absorption which was interpolated across during the reductions. Table 1 presents a log of the observations.

## 2.2. Optical Spectroscopy

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Optical spectroscopy of SDSS J1212 were also obtained at the Kitt Peak National Observatory 4-m telescope using RCSPEC. The observations took place on 4 June 2007 UT and used the KP-18C grating in first order a GG-385 order separation filter and the T2KB CCD. The slit width was set to 1", to match the seeing, and spectral coverage was 5500 to 7500 , with a resolution of 3 . This setup combination provided 1000 coverage at 1.3 resolution. The night was clear with photometric conditions and stable  $\sim 0.7$  arcsec seeing, allowing extraction of good-quality relative fluxes from the observations. SDSS J1212 was observed using 600 sec exposures over a total time period of 2.2 hours or 1.5 orbital periods.

## 2.3. Optical Photometry

Optical photometry was obtained for Tau 4 and EI Psc. EI Psc was observed using the 0.9-m telescope on Kitt Peak on 15 & 16 Dec 2006. Tau 4 was observed at the 0.9-m and the WIYN 3.5-m telescope, also located on Kitt Peak, on the nights of 9, 14, & 15 Dec 2007. The two 0.9-m nights were clear with  $\sim 1.1$  arcsec seeing, fairly typical for this telescope, while the 3.5-m night had cirrus present throughout all the observations. All the 0.9-m observations were all made using the S2KB CCD while the 3.5-m observations used the new prototype OTA imager QUOTA (reference). Table 2 provides a log of the

photometric observations.

### 3. Analysis

#### 3.1. Tau 4

Tau 4 (RX J0502.8+1624) is a cataclysmic binary of unknown orbital period suspected of being a magnetic system based on its optical spectrum, and X-ray hardness (Motch et al., 1996). The optical spectrum revealed a He II to H $\beta$  line ratio typical of polars (Warner 1995) but not exclusive to them (Kii et al. 1990). Hoard et al. (2002) identified the infrared counterpart and the 2MASS J-H and H-K colors placed Tau 4 in the region occupied by late L dwarfs.

Littlefair et al., (2005) obtained a single, short (900 second) K band spectrum of Tau 4 which presented a very odd shape over the 2 to 2.4 micron wavelength range. Their spectrum was unlike an L dwarf or a typical interacting binary, showing no spectral features at all. Instead, it presented only a hump-like shape over the K band, peaking near 2.25 microns. Littlefair et al., concluded that the K band light was dominated by cyclotron emission from a highly magnetic primary white dwarf apparently confirming Tau 4 as a polar. They did not suggest a magnetic field strength or which cyclotron harmonic they were viewing.

Many magnetic CVs do show IR colors dominated or modulated by cyclotron features, colors that are not direct measures of their secondary stars. The short-period polar EF Eri (Campbell et al., 2007) is such an example. EF Eri lies alone in an IR 2-color diagram; no other mass transferring interacting binary has yet been found to have such odd IR colors. We note that EF Eri has been in a low state (i.e., no mass transfer) for over a decade now and its IR colors are solely due to cyclotron emission throughout its orbit; no secondary

star contribution is present (see Brinkworth et al., 2007). Generally, the combination of cyclotron emission and secondary star flux in the near-IR will produce colors for magnetic interacting binaries that are near the M and L sequences but can often mislead users by inferring an incorrect spectral type for the actual secondary star present. The idea that pure cyclotron emission in the optical or near-IR produces non-stellar colors has been put to good use in the Sloan survey whereas odd colors can be used to find binaries whose optical flux is just cyclotron emission, i.e., the so-called LARPs (Schmidt et al. 2007, 2008).

### *3.1.1. Optical Photometry*

Figures 1 & 2 show our light curves for Tau 4 obtained a few months before the IR spectrum discussed next. Each of the three light curves show similar large brightness changes that seem to occur at apparent random times. The nature and amplitude of the large brightness changes seen for Tau 4 are broadly consistent with polar light curves. In typical polars, the photometric signatures are often identified with the active accretion pole on the primary white dwarf coming in and out of view. However, in most polars, the brightness modulations are both highly repeatable and consistent in shape and duration from orbit to orbit and can be used to define the binary orbital period. Tau 4 seems to show similar type changes but in a haphazard way. No apparent periodicity is observed in any of our light curves.

### *3.1.2. Infrared Spectroscopy*

IR spectroscopy was obtained for Tau 4 using Keck II and NIRSPEC. The observations consisted of 5 ABBA nods using integration times of 240 seconds (nod 1) and 180 sec for the remaining 4 nods. The total time coverage for all 5 nod sets was 80 minutes. If Tau 4 is

a short-period polar (i. e.,  $P_{\text{orb}} < 125$  min as most polars are) this time coverage was close to one complete orbital period for the binary. Each set of ABBA nods were combined into a single spectrum and finally all were combined into a single final spectrum to provide good S/N. Figure 3 shows the final summed Tau 4 K band spectrum.

Each summed nod group of spectra were examined and all looked similar to the final spectrum presented in Figure 3. At no time did we see a spectrum that had the K band shape or overall characteristics such as that presented in Littlefair et al. (2005). Instead, we find a K band spectrum much as expected for a short period interacting binary, that is, emission lines from an accretion disk or stream overlying a typical late-type dwarf spectral shape. We find no evidence for any absorption features, including Na, Ca, or CO, but the continuum S/N is rather low as the K band magnitude is estimated to be near  $K=17$ . The usual CO break in the continuum, observed at  $2.29 \mu\text{m}$  and usually rather strong in late-type dwarfs, is absent in our data. The lack of its presence could be a S/N issue, although this is not likely as the continuum break is usually a 30-50S/N. Another possibility is that CO is simply not present in the low mass donor star as observed for most dwarf novae type systems (see Harrison et al., 2003).

The relatively low spectral resolution and need for summing spectra disallowed any attempt to try to measure velocity variations for the H and He emission lines. The emission lines of  $\text{Br}\gamma$  and He I ( $2.05 \mu\text{m}$ ) have FWHM values of 960 km/sec; values that are fairly typical for an inclined accretion disk or possible a gas stream viewed in projection. We can not rule out a magnetic nature or the presence of an accretion disk in Tau 4, but we can say that none of our spectra show any evidence for cyclotron humps as were previously reported.

### 3.2. SDSS J1212

SDSS J121209.31+013627.7 is a  $g=18$  binary first studied in detail by Schmidt et al. (2005) and found to be a detached short period binary consisting of a cool white dwarf and a probably brown dwarf-like secondary star. The white dwarf is magnetic, having a dipolar field strength of 13 MG, and a surface temperature near 10,000K (Schmidt et al., 2003). We note here that J1212 is very similar to the polar EF Eri (Howell et al. (2006). Schmidt et al. (2005) observed Zeeman splitting of the white dwarf Balmer absorption lines and a narrow  $H\alpha$  emission line present for about one-half of the orbital period. The authors attributed this line to irradiation of the low mass secondary by the white dwarf. The semi-amplitude of the  $H\alpha$  line was 320 km/sec and suggested a mass for the secondary star near  $0.08 M_{\odot}$  likely to be a brown dwarf-like star. Hoard et al. (2007), using 5-14 micron spectroscopy of EF Eri, determined that the best fit secondary star in the system would be similar to an L5 star.

Near-IR light curves of J1212 obtained by Debes et al. (2006) revealed a highly modulated K band flux over the orbit and their analysis suggested an L7 dwarf companion to the white dwarf with the modulation being due to cyclotron emission. Burleigh et al. (2006) present optical photometry which again reveals the similarity to EF Eri, showing a “hot spot” modulation in all bands (u to i) equal to the 88.43 minute orbital period. Recent work by Farihi et al. (2008) confirm the secondary star characteristics as near those of a L8 substellar dwarf with the K band flux excess being modeled as the  $n=6$  and 7 harmonics of a  $B=7\text{MG}$  mean surface magnetic field on the white dwarf.

### 3.2.1. Optical Spectroscopy

We observed J1212 for approximately one-third of an orbital period using the Lick Observatory 3-m Shane reflector (see Table 1). The Lick double spectrograph provides simultaneous red and blue spectra which we present in Figure 4. Our Kitt Peak 4-meter spectra were obtained over 1.5 orbits of J1212 and are shown in Figure 5. The spectra in Figures 4 and 5 are phased on the photometric ephemeris given in Debes et al. (2006) where phase 0.0 was taken as the mid-point of the faint ( $K=17.3$ ), flat part of the K band light curve.

The overall appearance of the optical spectrum of J1212 is similar to those presented in Schmidt et al. (2005) in terms of the Zeeman splitting seen in the Balmer lines, the general flux levels, and the general continuum shape. The Lick spectra (Figure 4) are shown for five distinct orbital phases covering about 30 minutes (1/3 of the orbit). The spectra show a lack of emission features but a highly chopped continuum (especially in the blue) caused by the Zeeman split white dwarf Balmer absorption lines. The 4-meter spectra seen in Figure 5 cover 1.3 orbits and are displayed in time order. We do not see any  $H\alpha$  emission in the 4-meter spectra such as those reported in Schmidt et al. (2005). There *may* be very weak, narrow  $H\alpha$  emission visible in a few of the 4-meter spectra (e.g., phases 0.909, 0.028, and 0.384 in Fig. 5) which might indicate a weak but variable emission line or may be simply noise. Given the complete lack of any confirmed emission, we can rule out irradiation as the cause of the  $H\alpha$  emission previously observed.

If we sum the entire set of 4-meter spectra, we can measure the Zeeman splitting at  $H\alpha$  and, like Schmidt et al. (2005), a simple linear Zeeman fit to the two  $\sigma$  and the unshifted  $\pi$  split  $H\alpha$  absorption line components yields a magnetic field strength of  $6.7 \pm 0.5$  MG. We see no changes to the Zeeman splitting as a function of orbital phase (see figures 4 & 5), so we take this Zeeman determination as the mean surface field strength of the white dwarf.

We note that this value agrees with the field strength determined from model fits by Farihi et al. (2008).

### 3.2.2. *Infrared Spectroscopy*

Farihi et al. (2008) presented near-IR spectroscopy obtained with GNIRS on Gemini-South. They use these spectra, along with optical and near-IR photometry, to model the spectral energy distribution of J1212. Our K-band spectrum of J1212 obtained with NIRSPEC on Keck II is shown in Figure 7. Due to the faintness of J1212 in the K band, ( $K \sim 17$ ), both the Farihi et al. spectrum and ours shown in Figure 7 are sums over about two orbits of the binary. Our spectrum of J1212, obtained  $\sim 1$  year after that presented by Farihi et al., agrees well with theirs and indicates that J1212 has remained in a quiescent state during the time interval. Neither K-band spectrum shows any evidence of emission or absorption features. We also are happy to see that the two telescope/instrument combinations produce highly similar results.

## 4. Conclusion

Tau 4 presents a highly variable light curve at optical wavelengths but none of our observations show any indication of a periodic signal. Our K-band spectrum bears no resemblance to that presented in Littlefair et al. (2005) in that we see nothing looking like a broad cyclotron hump not a continuum rising to the red. Instead, our Tau 4 K-band spectrum is consistent with an interacting binary showing emission coming from an accretion disk or possibly a magnetically controlled gas stream between the stars. We see no absorption features in the K-band spectrum, but the continuum is of modest S/N. We can not rule out a magnetic nature for Tau 4, but it may well be a dwarf novae type binary

containing a non-magnetic white dwarf and an accretion disk. If true, the X-ray properties and highly variable optical light curve are interesting features of this star.

J1212 is again seen as a short period, white dwarf - brown dwarf-like binary star. Our new optical spectroscopy reveals Zeeman split Balmer lines from the magnetic white dwarf and indicate a mean surface field of  $\sim 7$  MG. No emission features are seen in any of our spectra covering over 2 orbits of the star on two separate occasions. Schmidt et al. (2005) noted the presence of  $H\alpha$  emission during about one-half of the orbit and attributed it to irradiation of the secondary star by the white dwarf. Numerical calculations of the needed energetics (Howell et al., 2006, 2008) and detailed model atmosphere fits (Mason et al., 2008) reveal that irradiation of the secondary star by the white dwarf in interacting binaries is unlikely to be important for systems in which the white dwarf has an effective temperature of less than about 20,000K. The white dwarf in J1212 has an effective temperature of 10,000K and along with the current observed lack of  $H\alpha$  emission argue that irradiation is not a factor in J1212 and was not the cause of the previously observed  $H\alpha$  emission.

As we alluded to, J1212 is very similar to the polar EF Eri (Howell et al., 2006). EF Eri has been observed with no emission lines present in its optical spectrum as well as with them. Howell et al. (2006) argue that the emission is related to magnetic interactions between the two stars and/or stellar activity like phenomena occurring on the low mass secondary star. When discovered, EF Eri had a high level of mass transfer between the stars and its optical spectrum was dominated by broad, large emission lines from H and He. For the last 12 years, EF Eri has shown no strong emission lines, only weak lines that come and go. During times of no to weak emission, EF Eri and J1212 are virtual twins. They both contain magnetic white dwarfs, brown dwarf-like secondary stars (near L5-L8), short orbital periods, and cyclotron dominated near-IR continua.

It has been suggested that J1212 is a pre-polar (Schmidt et al. 2005), that is, a binary system that currently is detached but will (astronomically) soon come into contact. This occurrence would then transform J1212 into a polar. However, EF Eri was a polar when discovered and now looks like the detached binary J1212. So, the direction of evolution of these two binaries and their future fate are far from understood.

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Table 1. Log of Spectral Observations

Star	Telescope	UT Date	Wavelength	Int. Time (sec)	N <sup>a</sup>
Tau 4	Keck II	5 March 2007	2.04-2.40 $\mu\text{m}$	240/180	10
J1212	Keck II	4 March 2007	2.04-2.40 $\mu\text{m}$	300	10
J1212	Lick 3-m	3 May 2007	3700-5500 / 6000-8500	600/900	5
J1212	KPNO 4-m	4 June 2007	5800-7800Å	600	12

<sup>a</sup>N = The number of spectra obtained.

Table 2. Log of Photometric Observations

Star	Telescope	UT Date	Filter	Int. Time (sec)	N <sup>a</sup>
Tau 4	KPNO 3.5-m	9 Dec 2006	R	300	22
	KPNO 0.9-m	14 Dec 2006	I	240	25
	KPNO 0.9-m	15 Dec 2006	V	240	40

<sup>a</sup>N = The number of frames recorded.

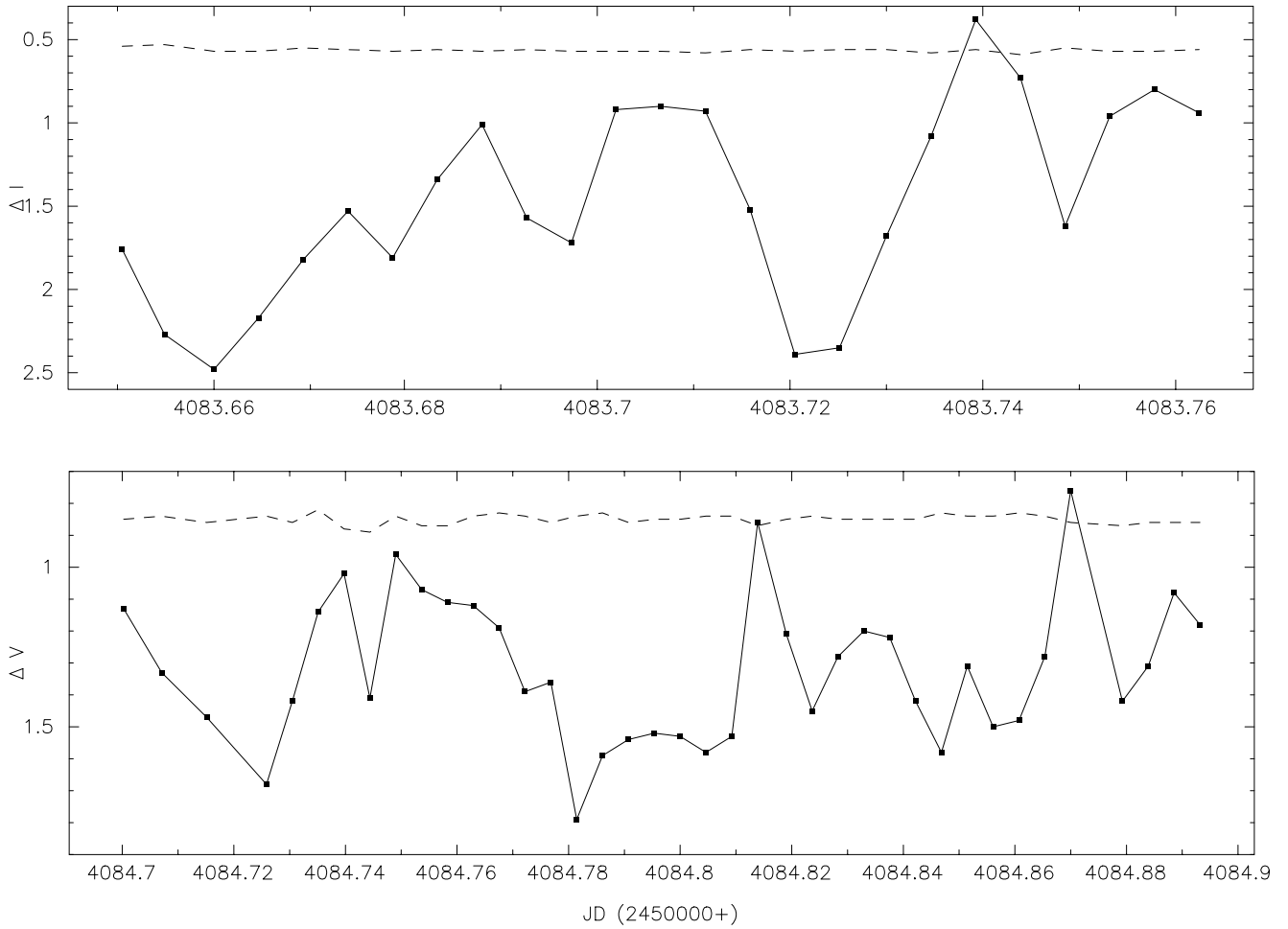


Fig. 1.— Differential light curves (14 Dec. 2006 UT I band top, 15 Dec. 2006 UT V band bottom) of Tau 4 observed with the Kitt Peak 0.9-m telescope. The dashed lines show the difference (C-K) light curves of two nearby, similar brightness stars providing a measure of the photometric uncertainty in these data. Note the large, apparently random brightness fluctuations in Tau 4.

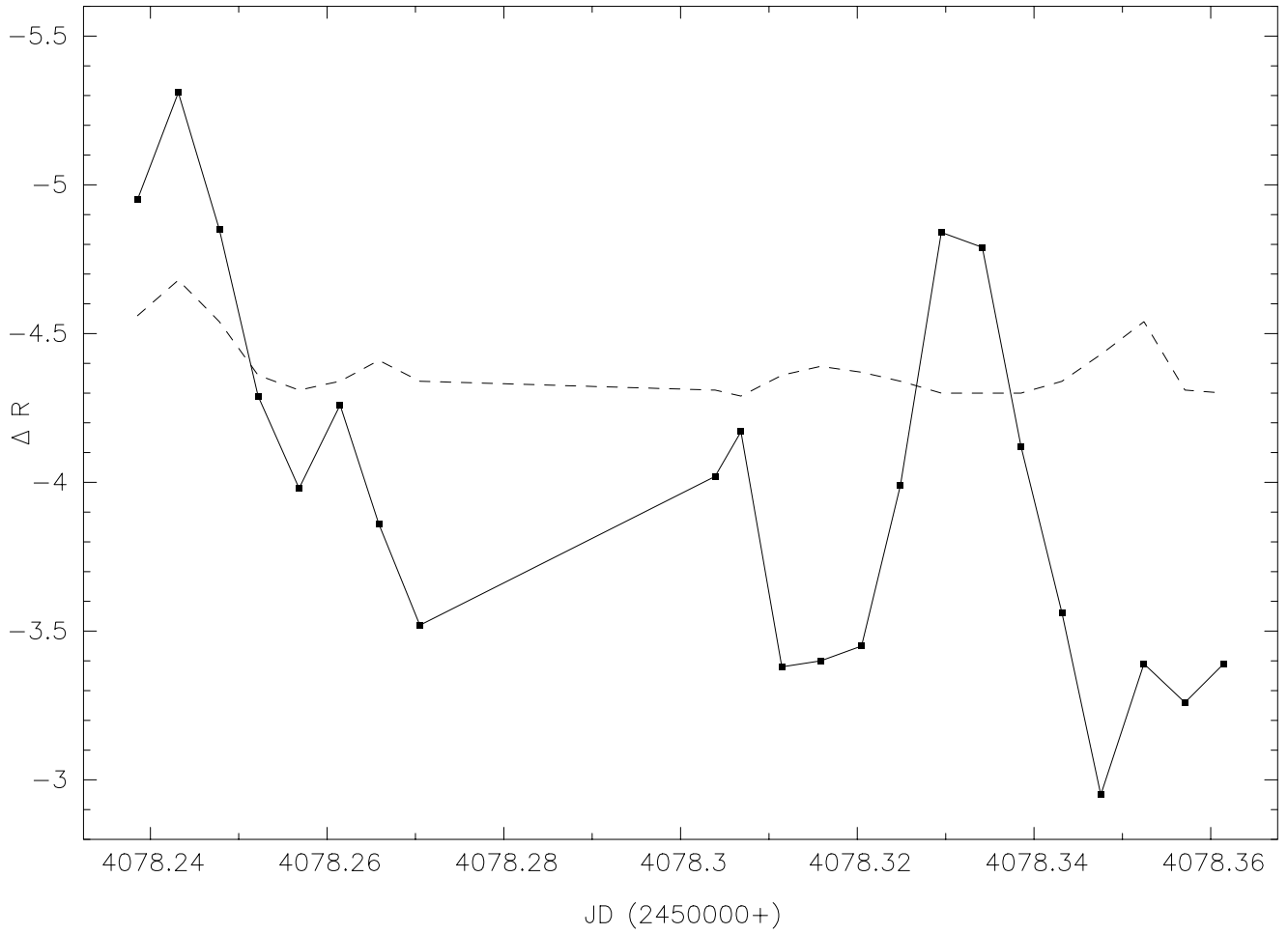


Fig. 2.— Differential light curve (9 Dec. 2006 UT R Band) of Tau 4 observed with the WIYN 3.5-m telescope. The dashed line shows the difference (C-K) light curve of two nearby, similar brightness stars providing a measure of the photometric uncertainty in these data. Note the large, apparently random brightness fluctuations in Tau 4.

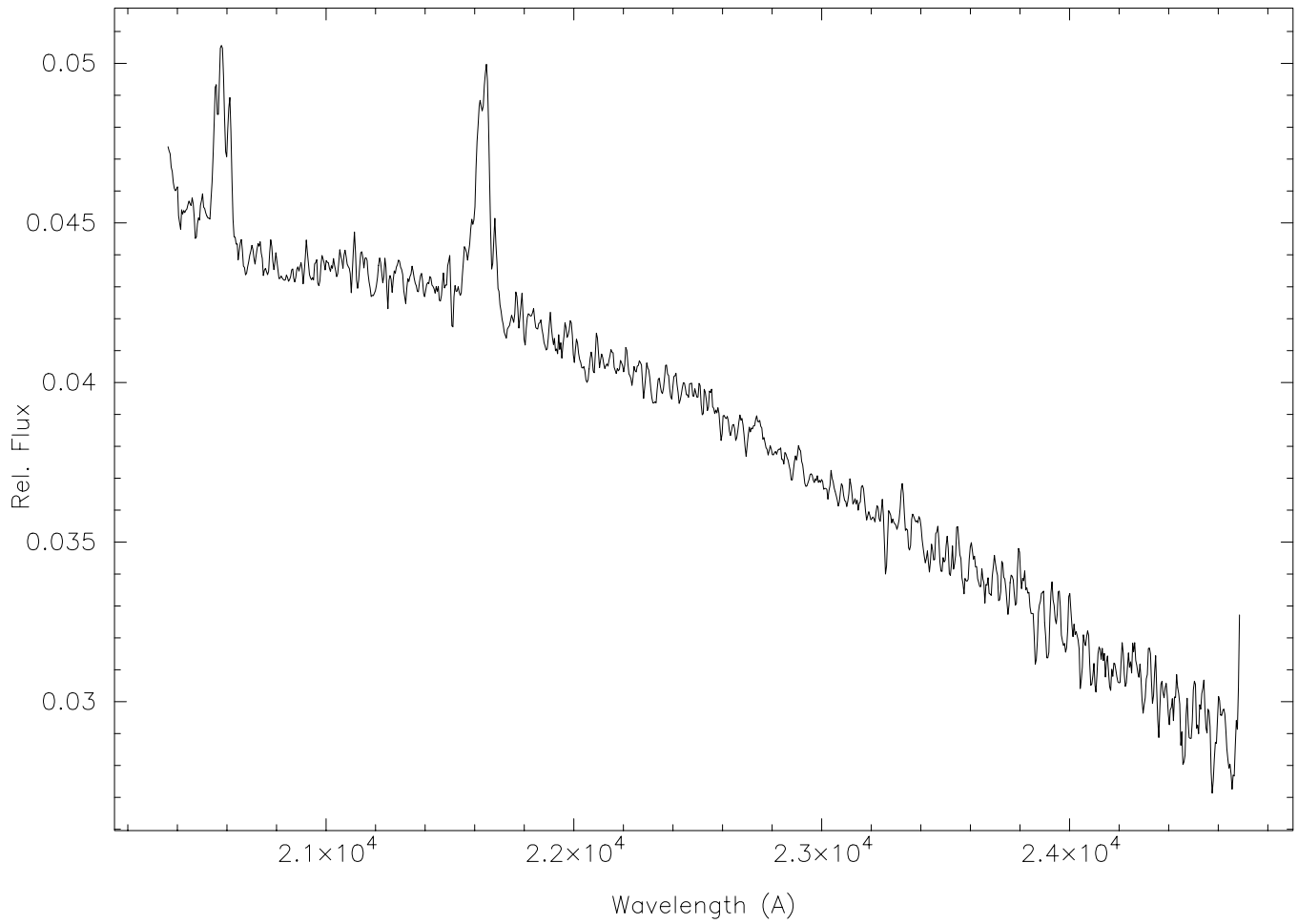


Fig. 3.— Keck II NIRSPEC K-band spectrum of Tau 4. The spectrum shows the usual accretion process emission lines due to hydrogen ( $\text{Br}\gamma$ ) and He I and a falling red continuum typical of a late-type main sequence or L dwarf in a short-period interacting binary. No absorption features are observed.

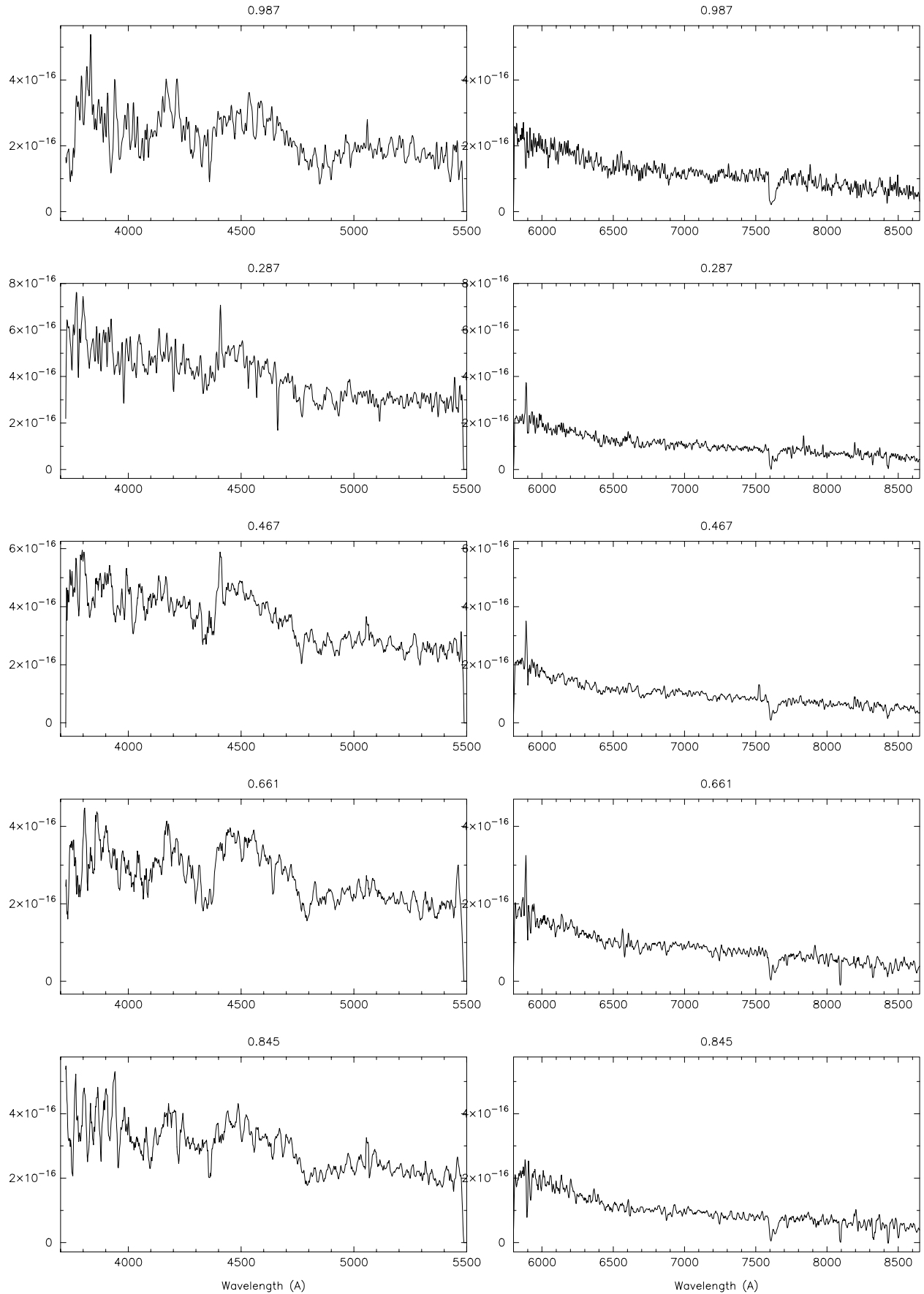


Fig. 4.— Lick Spectra of J1212 arranged by orbital phase showing each pair of simultaneous blue and red spectra. Note the lack of emission lines throughout and the Zeeman splitting of the Balmer lines.

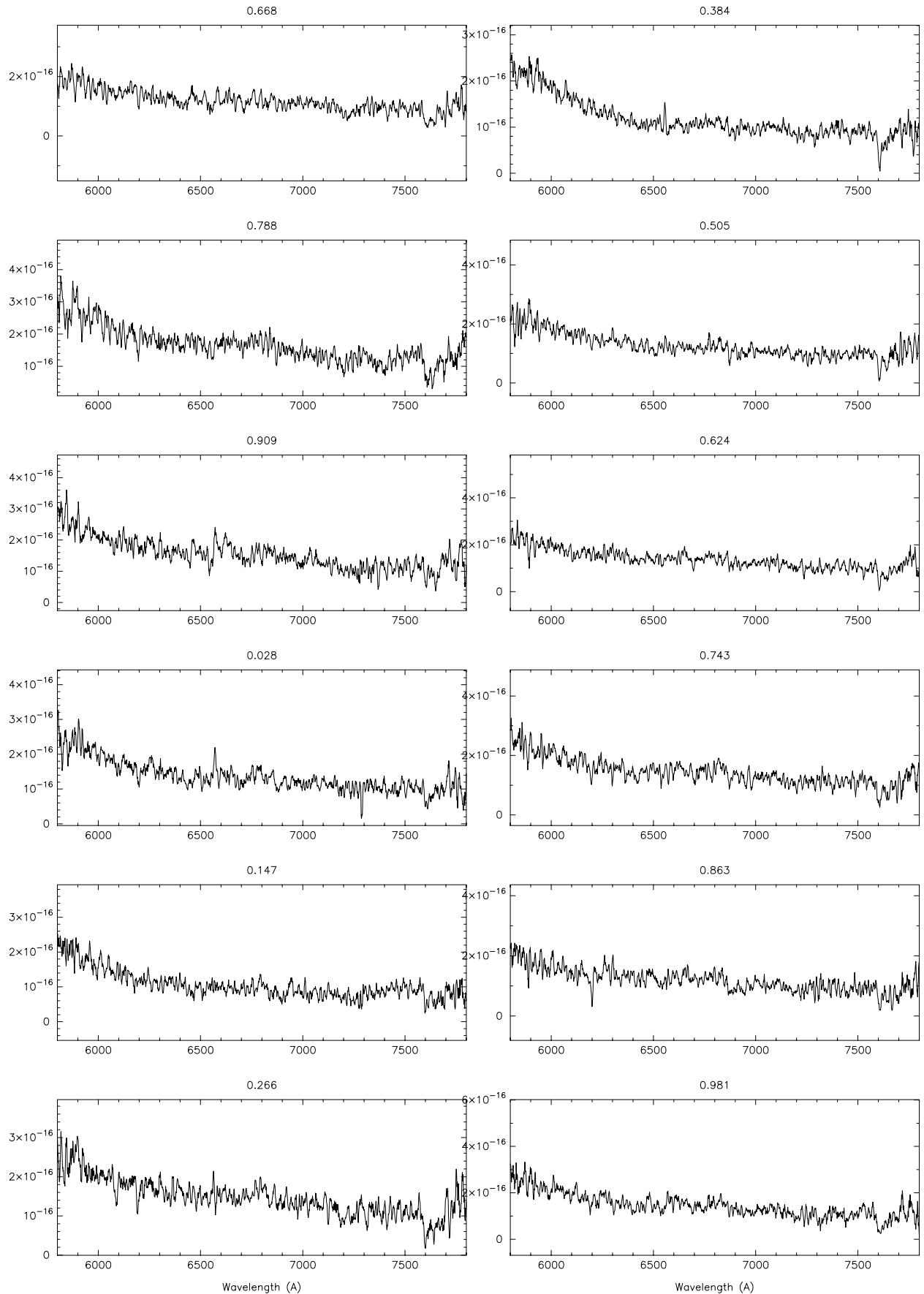


Fig. 5.— KPNO 4-m spectra of J1212 arranged by orbital phase in order of observation. The Zeeman split  $H\alpha$  components are weak in each individual spectrum and no emission is

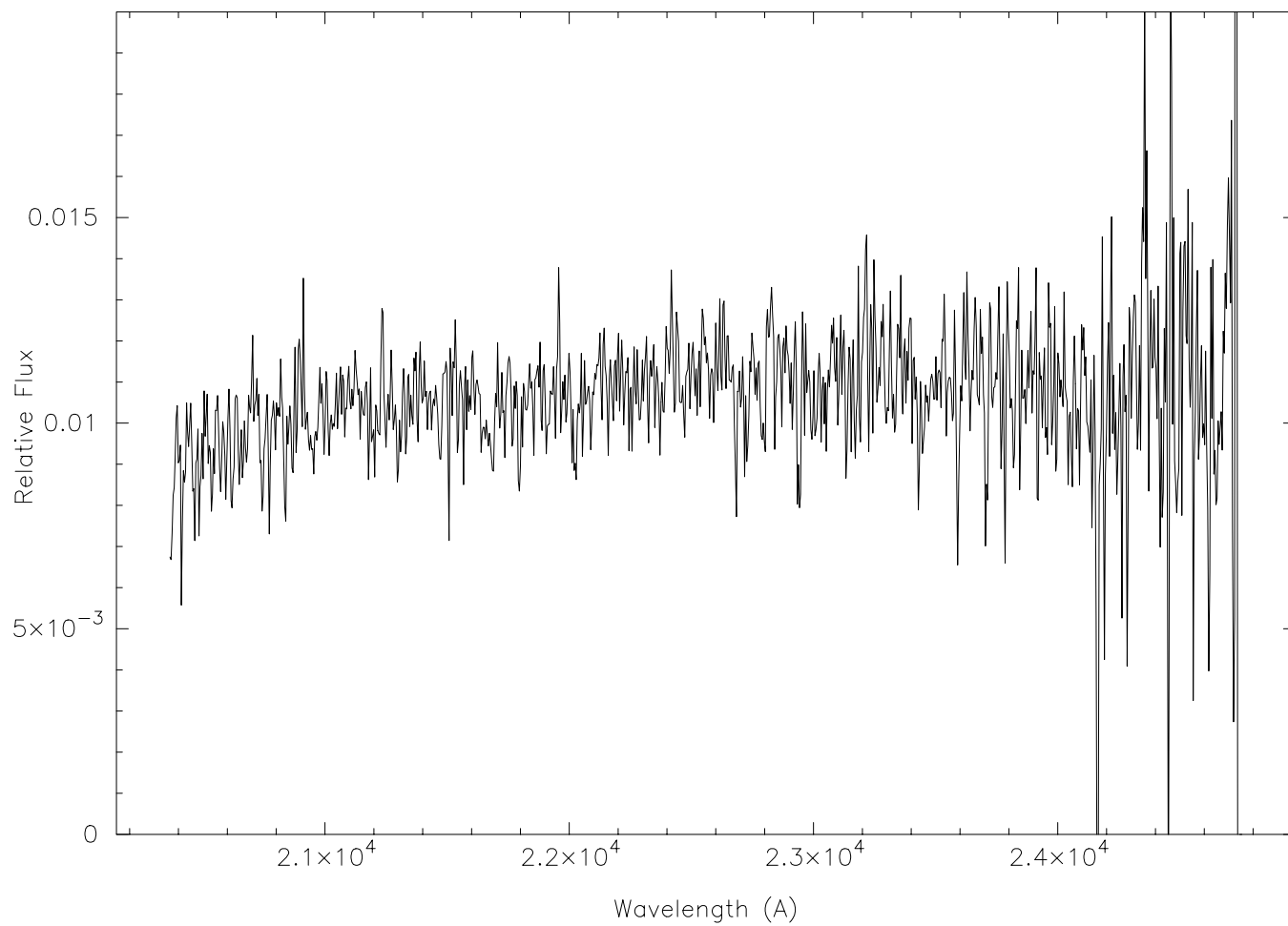


Fig. 6.— Keck II NIRSPEC K- band spectrum of J1212 summed over 80 minutes. The flat featureless K-band spectrum is caused by cyclotron emission and no features of the secondary star are seen.