Accepted for publication in The Astrophysical Journal

THEORETICAL SPECTRA OF THE AM CVN BINARY SYSTEM SDSS J0926+3624 : EFFECTS OF IRRADIATION ONTO THE DONOR STAR

Sujan Sengupta[1,2], and Ronald E. Taam[2,3]

ABSTRACT

Taking into account a range of parameters determined from the evolutionary models and available observational data, the detailed non-LTE spectrum for the primary star and the irradiated donor star in the AM CVn system SDSS J0926+3624 are constructed based on the TLUSTY stellar atmosphere code. The combined spectrum of the primary and the donor stars along with a multi-color blackbody spectrum of the accretion disk that reproduces a detailed numerical model is compared to the SDSS optical spectrum of the system. The photometric flux of the primary star inferred from eclipse observations is compared with the synthetic spectrum. The model fit of the two independent observations provides an upper limit on the distance of the system for different effective temperatures of the primary. In addition, an upper limit on the combined flux of the disk and the donor in the infrared region wherein the contribution of the primary is negligible is also determined. It is shown that the spectrum of a sufficiently cool donor can exhibit emission lines due to irradiation from a hot primary and the emission features should be detectable in the infrared even though the contribution of the flux from the disk dominates. Thus, it is pointed out that infrared observations of the system would provide important information on the thermal state of the donor as well as useful insight on the thermal properties of the primary star and the accretion disk.

---

[1]Indian Institute of Astrophysics, Koramangala 2nd Block, Bangalore 560034, India; sujan@iiap.res.in

[2]Academia Sinica Institute of Astronomy and Astrophysics - TIARA, P.O. Box 23-141, Taipei, 10617 Taiwan, R.O.C.

[3]Northwestern University, Department of Physics and Astronomy, 2131 Tech Drive, Evanston, IL 60208, USA; r-taam@northwestern.edu

Subject headings: binaries: close — binaries: eclipsing — stars: individual (SDSS J092638.71+ 362402.4) — stars: atmospheres — stars: low mass — stars: white dwarfs

1. INTRODUCTION

The only known eclipsing AM Canum Venaticorum object to date, SDSS J0926+3624 (Anderson et al. 2005), belongs to the class of ultra compact binary systems characterized by a pair of interacting white dwarfs with the shortest orbital period among any other binary subclass. Such a system is driven by the loss of orbital angular momentum by the emission of gravitational waves and is among a class of systems thought to constitute the largest fraction of interacting ultra compact binaries in the Galaxy [see Nelemans, Yungelson & Portgies Zwart (2001, 2004)]. An understanding of their properties is important for their detectability not only as individual candidate sources, but also as background sources of low frequency gravitational waves [e.g.,Nelemans, Yungelson & Portgies Zwart (2004); Stroeer, Vecchio & Nelemans (2005)].

A detailed understanding of the formation of SDSS J0926+3624 (hereafter J0926+3624) also allows one to place important constraints on the efficiency of the common envelope phase of binary evolution in forming short period binary systems containing double white dwarf components [e.g., Nelemans & Tout (2005); for a review of the common envelope phase of evolution for the general binary population, see Iben & Livio (1993); Taam & Sandquist (2000)]. For AM CVn systems, in general, their formation may involve a white dwarf or helium star channel (Nelemans, Yungelson & Portgies Zwart 2001), or an evolved hydrogen main sequence star channel (Podsiadlowski, Han & Rappaport 2003). As shown by Deloye et al. (2007) their subsequent evolution is affected by the thermal state of the donor star.

The observational investigation of these double white dwarf systems provides important insights into their nature and formation. For example, optical observations of the line spectrum from the system carry the combined physical and chemical properties of the accretor and the accretion disk while infrared observations of the spectrum may provide important constraints on the thermal state, chemical composition, and surface gravity of the donor. As a result, atmospheric studies of the donor in combination with knowledge of its distance can be used as an additional probe of the formation channel and evolutionary state of the system (Roelofs et al. 2007).

J0926+3624 offers a unique opportunity for probing the thermal properties of the donor star since its surface gravity, essential for calculating the synthetic spectrum, is known. In addition, the orbital separation between the accretor and the donor, which determines the amount of irradiation onto the donor, is known from the component masses and orbital period.

In this Letter, we present the model composite spectra consisting of the non-LTE spectra of an irradiated donor, and a primary star as well as a multi-color blackbody spectrum of the accretion disk. The model parameters for the system are discussed in §2. The formalism for estimating the contribution of the accretion disk is also discussed in this section. In §3, a brief description of the numerical methods employed for calculating the non-LTE theoretical spectra of both the accretor and the donor stars is provided. The results are described and discussed in §4 followed by our conclusions in the last section.

2. ATMOSPHERIC MODEL PARAMETERS

The range for most of the model parameters of J0926+3624 is constrained by the modelling of eclipse light curves. Based on the theoretical work of Bildsten et al. (2006) and the observational study of Copperwheat et al. (2011) the mass range of the primary (donor) is estimated as $0.79 - 0.89$ $M_{\odot}$ ($0.027 - 0.038$ $M_{\odot}$). Taking the mass of the primary and the donor stars as 0.84 $M_{\odot}$ and 0.029 $M_{\odot}$ respectively and the observed orbital period of 28.3 min, Deloye et al. (2007) estimate the radius of the primary to be 0.01 $R_{\odot}$ and the radius of the donor to be 0.043 $R_{\odot}$. Hence, we set the surface gravity of the primary at $\log(g) = 8.3$ and that of the donor at $\log(g) = 5.6$ where the surface gravity g is in cm s^{-2}. From the center-to-center distance and the radii of the components we find the surface-to-surface separation to be $1.67 \times 10^{10}\, cm$. For irradiation from the photosphere of the primary star onto the surface of the donor star, the surface-to-surface separation is considered in our calculations. Although the incident radiation impinges on one face of the donor, we consider complete redistribution of the irradiated heat energy over the entire surface of the donor. As the donor star is likely to be tidally locked with the primary star, its spin rotation period should be the same as the orbital period. The small orbital period and the relative sizes of the components would tend to establish a complete redistribution of irradiated energy over the entire atmosphere of the donor star. The flux difference of the day and night sides of Jupiter size exoplanets orbiting with a period of a few days ranges from 10% to 50% (Burrows, Ibgui & Hubeny 2008). In the case of an irradiated but self-luminous object with radius about an order of magnitude less than Jupiter and orbiting with a period as small as 28 mins, the difference in the irradiated and non-irradiated sides should be much less.

The effective temperature of both the primary and the donor remains uncertain owing to the absence of a direct measurement of the distance to the system. Recently, Copperwheat et al. (2011) estimated the contribution of the primary white dwarf star from the eclipse depth, measured from multi-band, high time resolution light curves of the system. By fitting the flux in the ultraviolet and optical bands with a synthetic spectrum they establish a lower limit to the effective temperature of the primary $T_{eff,P}$ as 17000K. In previous work, Deloye et al. (2007) and Bildsten et al. (2006) theoretically estimated $T_{eff,P}$ to lie between 21000K and 24000K based on its cooling and compressional luminosity. Deloye et al. (2007) also predict the effective temperature of the donor star $T_{eff,D}$ to lie in the range between 1750K and 4500K. Guided by the blackbody model of Deloye et al. (2007), we adopt three different $T_{eff,P}$ (18000K, 21000K and 25000K) and three different $T_{eff,D}$ (3800K, 4000K and 4400K).

The evolutionary model calculations by Deloye et al. (2007) estimate the accretion rate to be about 10^{-10} $M_\odot\, yr^{-1}$. There have been a few attempts to model the flux from the accretion disk (see Nagel, Rauch & Werner (2009) and references therein). However, all these models assume a steady state disk. Further, from the variation in the location of a bright spot, Copperwheat et al. (2011) found that the geometry of the outer disk departs from circular motion. A detailed non-LTE model of a non-steady state disk with non-circular geometry is beyond the scope of the present investigation. Therefore, we approximate the flux of the disk by considering

$$F_{disk} = \int_{R_{in}}^{R_{out}} 2\pi r B(r) dr \tag{1}$$

where $B(r)$ is the Planck function corresponding to the radial distribution of the effective temperature given by Nagel, Rauch & Werner (2009)

$$T(r) = \left[\frac{3GM_P\dot{M}}{8\pi\sigma r^3} \left(1 - \sqrt{\frac{R_P}{r}} \right) \right]^{1/4} \tag{2}$$

where M_P and R_P are the mass and the radius of the primary respectively, $\dot{M}$ is the mass accretion rate and σ is Stefan-Boltzmann constant. Following Nagel, Rauch & Werner (2009) we take the inner radius R_{in} of the disk equal to $1.3R_P$. The outer radius R_{out} is taken to be $0.45a$ which is the maximum value of the radius of the disk determined from the observation of Copperwheat et al. (2011) where a is the orbital separation. A composite blackbody spectrum reproduces the non-LTE steady-state accretion disk model of Nagel, Rauch & Werner (2009) well. The contribution of the disk to the total flux depends on the inclination angle and for the present object the inclination angle is as high as 83^o (Copperwheat et al. 2011). A comparison of the model spectra of Nagel, Rauch & Werner (2009) for different inclination angles implies that the flux should be reduced by a factor of 4 to 7 when the inclination angle is 83^o. Therefore, in order to obtain an upper limit on the contribution of the disk to the total flux, we assume that at 83^o inclination angle the flux is reduced by a factor of 4 as compared to its value at a face on view.

3. NON-LTE MODEL ATMOSPHERES

The stellar-atmosphere code TLUSTY developed by Hubeny and colleagues (Hubeny 1988; Hubeny & Lanz 1995) and the related spectrum synthesis code SYNSPEC (Hubeny, Hummer & Lanz 1994) are used for the investigation. In using this code, we have adopted the atomic data and model atoms provided on the TLUSTY homepage[1] (Lanz & Hubeny 2007, 2003). The atomic spectral line database from CD ROM 23 of R. L. Kurucz (Kurucz & Bell 1995) is used in SYNSPEC. The elemental abundances adopted are listed in Table 1. The elements whose abundance is less than 10^{-5} are ignored as they do not significantly contribute to the total opacity. We have included micro-turbulence at the level of $2 - 5\,kms^{-1}$ relevant for high effective temperatures (Lanz & Hubeny 2007). However, the overall spectrum is not altered even if this value is increased by a few times. For all the cases, the emergent flux is integrated over all frequencies and the energy balance was checked for self consistency corresponding to the effective temperature for models with and without irradiation.

In order to achieve convergent solutions for the atmospheric model of the donor star, we have neglected the effects of convection. However, comparison with a model calculated by using the atmosphere code PHOENIX [Barman, Hauschildt, Short & Baron (2000) and references therein] implies that convection affects the spectrum in the optical where the flux of the donor is negligible as compared to that of the primary or the disk.

TLUSTY is well tested and widely used for constructing the spectrum of both hot stars (Lanz & Hubeny 2007) and ultra-cool objects such as brown dwarfs (Burrows, Sudarsky & Hubeny 2006). We compared our results with a set of similar models, but with different elemental abundances constructed by using the atmosphere code PHOENIX. These models were kindly provided to us by F. Allard and D. Homier (private communication 2008).

4. RESULTS

Since the abundances of elements other than He are low, the opacity of the atmosphere of the donor as well as the primary is mainly determined by this constituent. Fig. 1 illustrates the thermal structure of the atmosphere of the donor star as a function of pressure for

[1]http://nova.astro.umd.edu/index.html

different levels of irradiation from the accretor. It can be seen that at a pressure of about 100 bar, the temperature increases rapidly. This rapid temperature increase occurs as the Rosseland mean optical depth exceeds unity. The total pressure varies slowly with respect to the optical depth as the optical depth increases from 1.2 at about 576 bar to 116 at about 667 bar for $T_{\mathrm{e}ff,D} = 3800$K. When irradiation is included, the temperature varies significantly at optical depths less than unity. For an effective temperature as low as 18000K for the primary and as high as 4400K for the donor, a few emission lines appear only in the infrared as can be seen from Fig. 2 (panel A). As the irradiation energy increases with the increase in the effective temperature of the accretor, the spectrum changes dramatically with the appearance of emission lines in both the optical and infrared wavelength regions (see panel B in Fig. 2). For a fixed orbital separation, the emission features in the spectrum of the donor not only depend on the effective temperature of the accretor, but also on that of the donor itself. As can be seen in panel B of Fig. 2, weak emission lines are apparent from the optical, e.g., at wavelength slightly greater than 0.5 μm to infrared if the donor is cooler ($T_{\mathrm{e}ff,D} = 3800$K) whereas strong emission lines are present in the entire spectrum if $T_{\mathrm{e}ff,P}$ is increased to 21000K and to 25000K even if the donor is hotter than 3800K.

The combined spectrum of the system is derived by multiplying the surface area of each component with its flux and then summing them up with the flux of the disk. In Figs. 3 and 4 we present the synthetic spectra of the primary and the irradiated donor, the composite blackbody spectrum of the accretion disk as well as the combined flux which is compared with the well calibrated and phase-averaged Sloan optical spectrum of the object. The observed spectrum from 0.38 to 0.92 μm is reproduced from the SDSS archival data. The flux of the primary at u′, g′ and r′ bands are also presented for a comparison. We have not performed any statistical analysis while comparing the synthetic spectra with the observed flux and our fit is by eye. In Fig. 3, we also compare our synthetic spectra with that constructed by using the atmosphere code PHOENIX. The overall agreement over the emergent flux in the entire wavelength region adopted in our investigation is considered as the evidence for a successful implementation of the TLUSTY and the SYNSPEC codes.

Fig. 3 shows that for a model characterized by $T_{\mathrm{e}ff,P} = 21000\,K$ and $T_{\mathrm{e}ff,D} = 4400\,K$, the SDSS spectrum matches if the distance of the system is about 495 pc and $\dot{M} = 1.5 \times 10^{-10}$ $\mathrm{M}_{\odot} yr^{-1}$. The object J0926+3624 has another component, a spot. Unfortunately, the nature and amount of flux contributed by the spot is not known. If the contribution of the spot is comparable to that of the disk or the primary, then the present fit of the SDSS data at 495 pc implies an upper limit of the flux from the accretion disk. On the other hand the observed flux of the primary is a few times less than the model flux of the primary. It should be noted that the observed data of the primary is not calibrated for extinction and therefore the actual flux may be slightly higher. Therefore, the distance needed to fit both the observed data may be considered as an upper limit. Figure 4 (panel A), however, shows that the non-calibrated observed flux of the primary fits well with a model characterized by $T_{eff,P} = 18000\,K$ if the distance is about 465 pc which is consistent with the analysis of Copperwheat et al. (2011). At a distance d=465 pc, the combined flux also fits well with the SDSS data if $T_{eff,D} = 3800\,K$. If the spot contributes significantly, then a decrease in the flux from the accretion disk is needed to fit the SDSS data at this distance. It is worth mentioning here that the observation of Copperwheat et al. (2011) doe not indicate that the flux of the spot is comparable to that of primary. The model characterized by $T_{eff,P} = 25000\,K$ and $T_{eff,D} = 4000\,K$ is apparently ruled out as the distance needed to fit the SDSS data is too high to fit the observed flux of the primary at the three optical bands. A single disk model as described in §2 is considered in all the above comparisons.

For the range of the donor's effective temperature between 3800K and 4400K and that of the primary between 18000K and 25000K, it is found that the flux of the donor dominates over that of the primary at wavelength greater than about $1.1\,\mu m$. However, the optimal flux of the accretion disk adopted in the present simplified blackbody model is higher than that of both the primary and the donor at all wavelengths. Therefore, future observation at infrared wavelengths will enable an estimate of the combined flux of the accretion disk and the donor. Since the mass and radius of the donor can be well constrained from the evolution model, infrared observation would provide an excellent opportunity to estimate a range of the properties of the accretion disk.

Further, an important finding in the present investigation is the appearance of emission lines in the spectrum of the donor due to the effect of irradiation. Figs. 3 and 4 also show that the combined flux does not dilute the emission feature originating from the donor's surface, even though the contribution from the disk is higher. This, however is not obvious for any combination of the effective temperature of the primary and the donor. As discussed earlier, the emission line strength becomes dominant when the temperature difference between the donor and the primary increases. In the shorter wavelength region, atomic scattering plays a dominant role over absorption. Therefore, the emission lines occur in the near optical region only if the irradiation is sufficiently strong so that the scattering albedo is much less than 1. However, the temperature-pressure profiles imply strong temperature inversion which indicates penetration of irradiation energy into the atmosphere even below the region where the optical depth is unity. In the region where the optical depth is comparable to unity, photons are absorbed and re-emitted in the infrared. Therefore, even with relatively weak irradiation, emission lines appear in the infrared. On the other hand, Nagel, Rauch & Werner (2009) obtained few emission lines in the spectrum of the disk for an accretion rate higher than 10^{-10} $M_{\odot} yr^{-1}$. Therefore, detection of emission lines in the infrared spectrum of the object would provide important insight on the atmospheric properties of the donor.

5. CONCLUSIONS

Theoretical spectra were calculated for the two white dwarf components in the AM CVn system J0926+3624 using the non-LTE atmosphere code TLUSTY and SYNSPEC. A range of effective temperatures is adopted based on estimates derived from theoretical binary evolutionary considerations for a system formed in the white dwarf channel. Irradiation of the cool donor star by the hot primary star is included by assuming complete redistribution of energy over the entire atmosphere of the donor star. Observations indicate the presence of a spot whose contribution to the total flux is unknown. In the absence of a self-consistent non-steady state disk model, a multi-color blackbody spectrum of the disk is considered and a maximum disk size is adopted as inferred from observation. Comparison of the total flux derived by the present models places upper limits on the distance of the object as well as the contribution of the accretion disk to the total flux. The present findings emphasize that future infrared observations of the system would provide a good estimation of the contribution by the accretion disk to the total flux and hence important insight on the thermal properties of the accretion disk. We also predict emission lines in the infrared wavelength region, originating from the spectrum of the irradiated donor. The width of these lines are dependent on the effective temperature of both the donor and the accretor and hence high resolution spectrum may be needed to detect them. If, however, the donor is sufficiently cool, as suggested by the evolutionary models, the emission lines could be detected easily providing an important diagnostic probe for the donor.

We thank the referee for valuable comments and suggestions that have improved the quality of this Letter. Thanks are due to C. Deloye for providing the Sloan optical data of SDSS J0926+3624 and to F. Allard and D. Homier for providing a set of PHOENIX models for comparison. SS thanks G. Pandey for help in implementing the TLUSTY and SYNSPEC numerical programmes. RT acknowledges support, in part, from NSF grant no. NSF AST-0703950 to Northwestern University.

REFERENCES

Anderson, S. F., et al. 2005, AJ, 130, 2230.

Barman, T. S., Hauschildt, P. H., Short, C. I., & Baron, E. 2000, ApJ, 537, 946.

Bildsten, L., Townsley, D. M., Deloye, C. J., & Nelemans, G. 2006, ApJ, 640, 466.

Burrows, A., Sudarsky, D., & Hubeny, I. 2006, ApJ, 640, 1063.

Burrows, A., Ibgui, L., & Hubeny, I. 2008, ApJ, 682, 1277.

Copperwheat, C. M. et al. 2011,MNRAS, 410, 1113.

Deloye, C. J., Taam, R. E., Winisdoerffer, C. & Chabrier, G. 2007, MNRAS, 381,525.

Hubeny, I, 1988, Computer Physics Communications, 52, 103.

Hubeny, I., Hummer, D. G., & Lanz, T. 1994, A& A 282, 151.

Hubeny, I & Lanz, T. 1995, ApJ, 439, 875.

Iben, I. Jr. & Livio, M. 1993, PASP, 105, 1373.

Kurucz, R. L. & B. Bell, 1995, Atomic Line Data, Kurucz CD-ROM No. 23. (Smithsonian Astrophysical Observatory : Cambridge, Mass.).

Lanz, T. & Hubeny, I. 2003, ApJS, 146, 417.

Lanz, T. & Hubeny, I. 2007, ApJS, 169, 83.

Nagel, T., Rauch, T., & Werner, K. 2009, A & A, 499, 773.

Nelemans, G., Yungelson, L. R., & Portegies Zwart, S. F. 2001, A & A, 375, 890.

Nelemans, G., Yungelson, L. R., & Portegies Zwart, S. F. 2004, MNRAS, 349, 181.

Nelemans, G., & Tout, C. A. 2005, MNRAS, 356, 753.

Podsiadlowski, P., Han, Z., & Rappaport, S. 2003, MNRAS, 340, 1214.

Roelofs, G. H. A. et al. 2007, ApJ, 666, 1174.

Stroeer, A., Vecchio, A., & Nelemans, G. 2005, ApJ, 633, L33.

Taam, R. E. & Sandquist, E. L. 2000, ARAA, 38, 606.

This preprint was prepared with the AAS LaTeX macros v5.2.

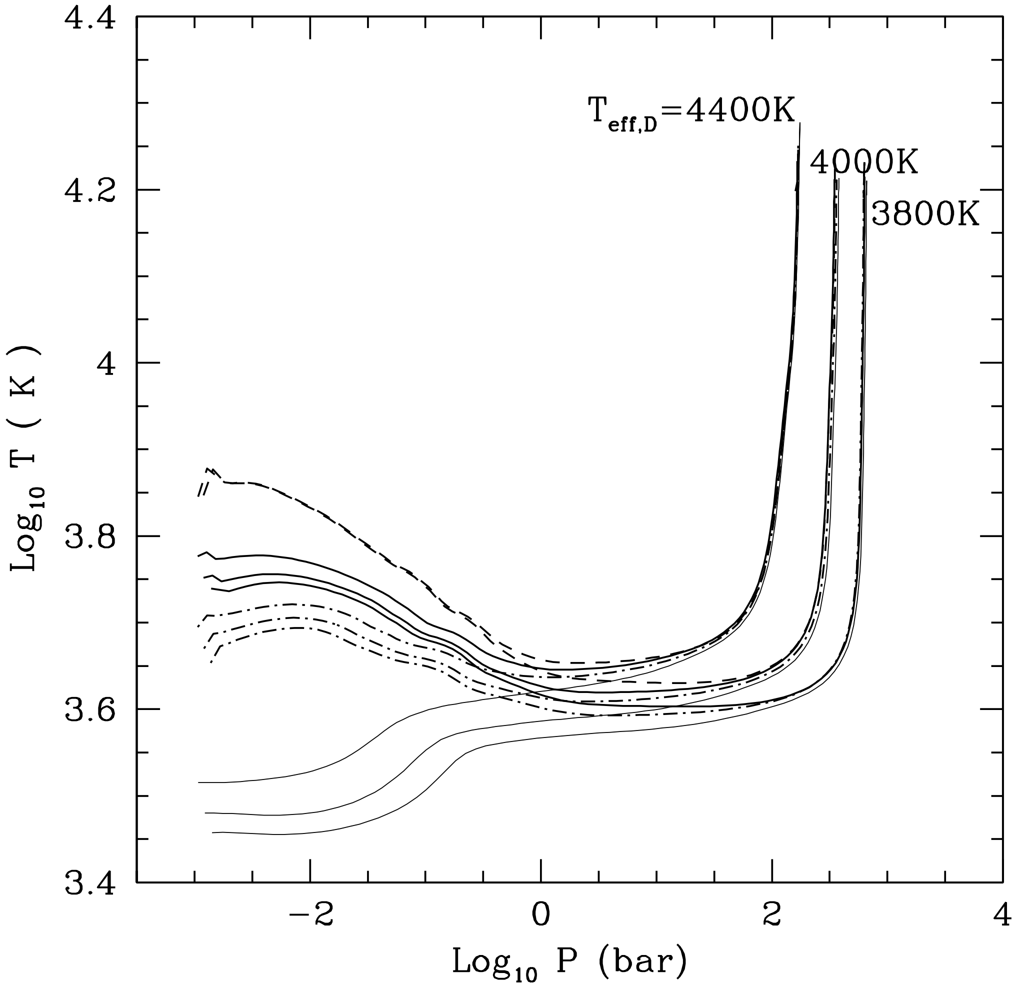

Fig. 1.— The Temperature-Pressure (T-P) profile of the donor star. The numbers near the lines indicate the effective temperature of the non-irradiated donor. The thin solid lines represent the T-P profiles of the non-irradiated donor while the thick solid lines represent that with irradiation from a primary with $T_{eff,P} = 21000\,K$ and the dashed line with $T_{eff,P} = 25000\,K$. The dash-dot lines represent the T-P profiles of the donor with irradiation from a primary of $T_{eff,P} = 18000\,K$.

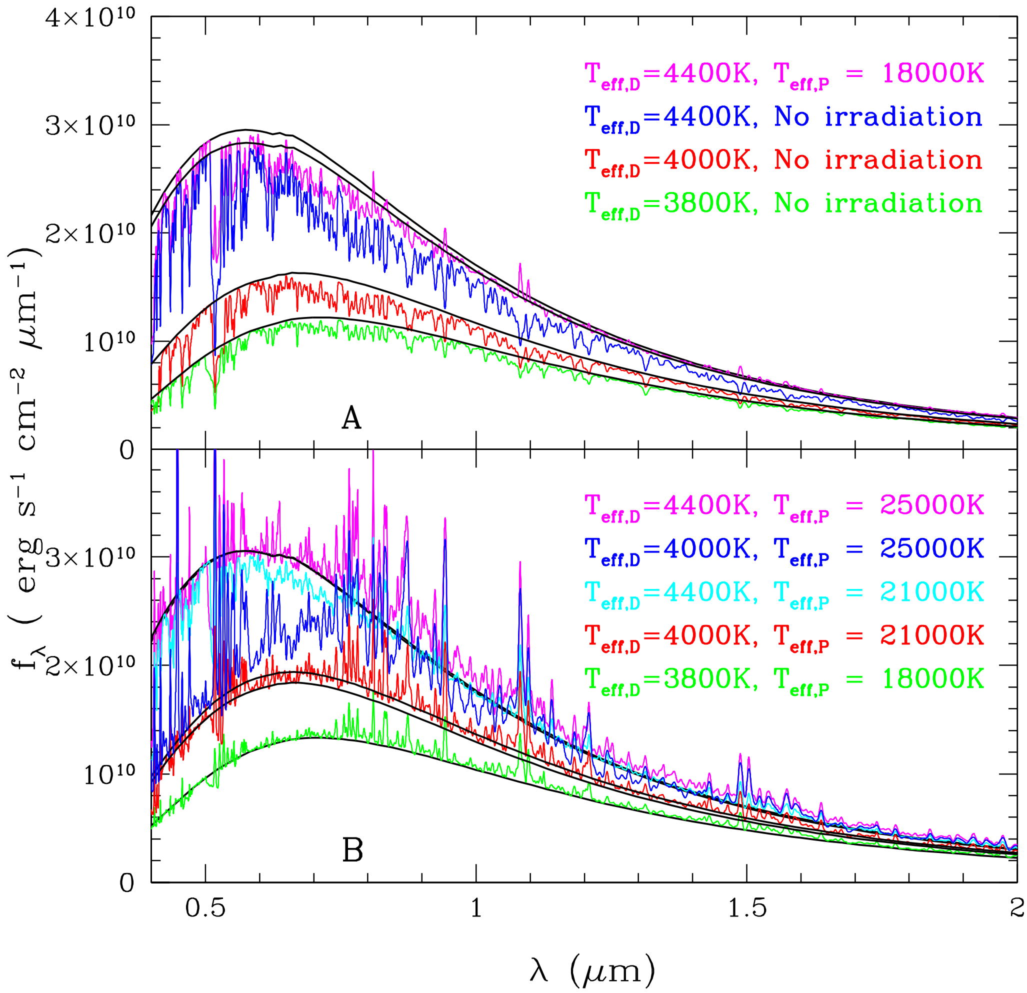

Fig. 2.— The synthetic spectra of the non-irradiated (panel A) and the irradiated (panel B) donor star. $T_{eff,D}$ is the effective temperature of the donor without irradiation and $T_{eff,P}$ is that of the primary which irradiates the donor. The black lines are the corresponding continuum flux. The model with $T_{eff,D} = 4400\,K$, $T_{eff,P} = 18000\,K$ is also included in panel A for a comparison with the non-irradiated case.

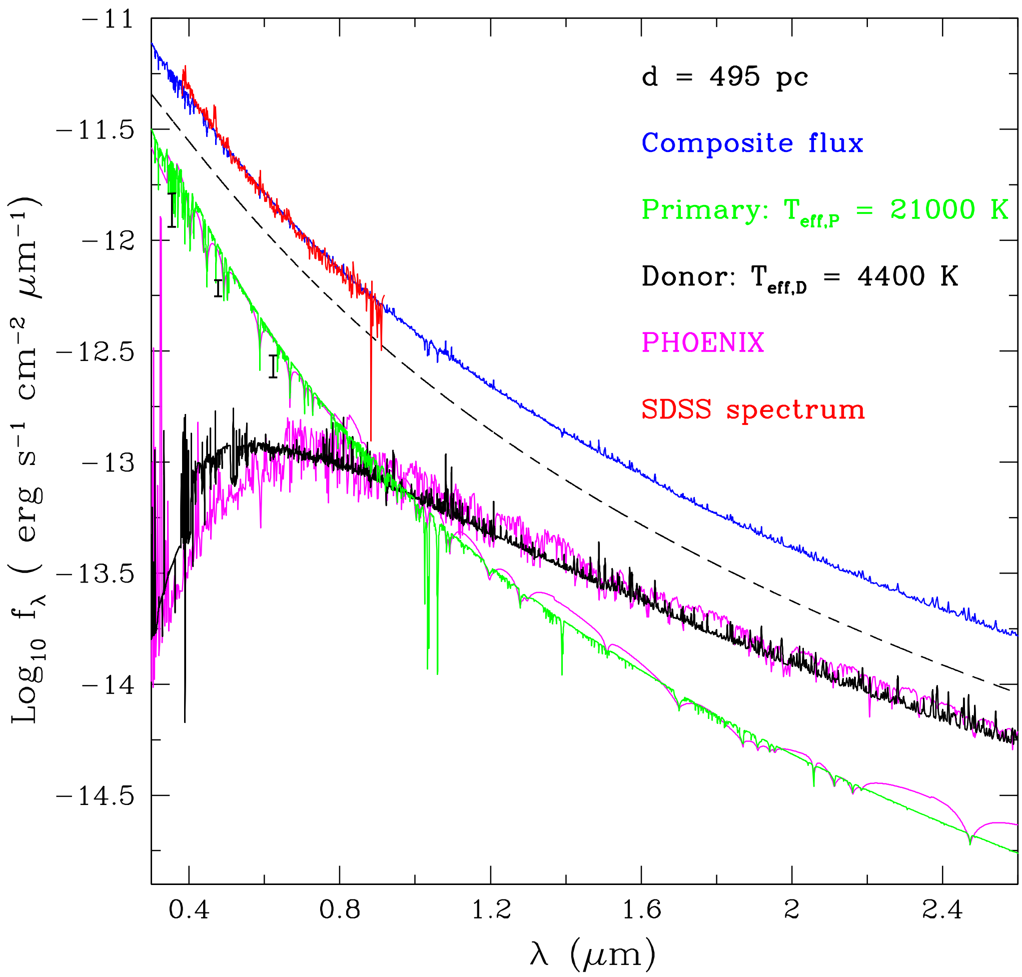

Fig. 3.— Model fit of the Sloan optical spectrum (red lines) as well as the photometric flux at u', g' and r' bands (black error bars). The green line represents the spectrum of the primary with effective temperature 21000 K and the black line represents that of the irradiated donor with $T_{eff,D} = 4400\,K$. The dashed line represents the composite blackbody spectrum of the accretion disk. The blue line is the combined spectrum of the accretion disk, the primary and the donor stars. The results (with different elemental abundances) from the atmosphere code PHOENIX are also presented for comparison.

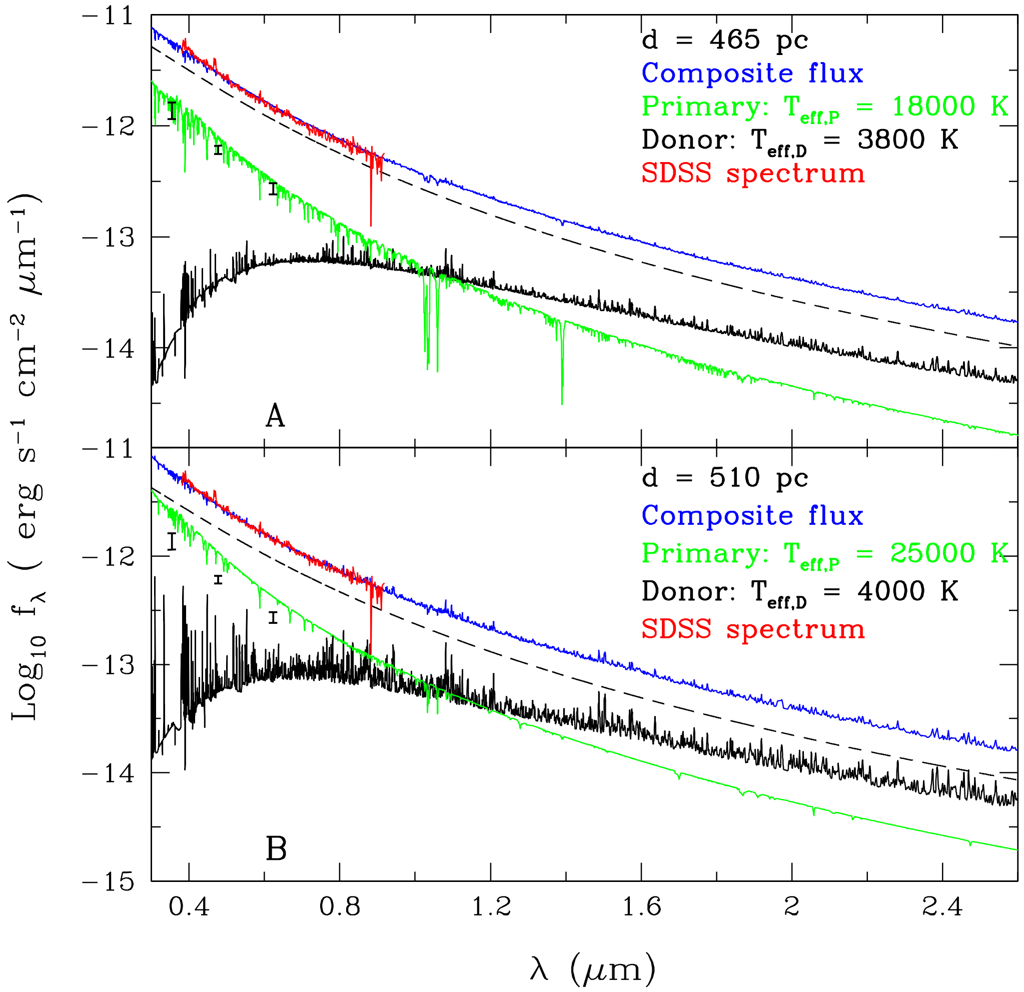

Fig. 4.— Same as figure 3 but with different effective temperature of the primary and the donor stars.

Table 1: The elemental abundances A by number with respect to He adopted for the models. Comparison with solar abundances as derived by TLUSTY is presented in column 3.

Element	A=N(element)/N(He)	A/A(Solar)
He	1.0	10.0
C	4.79×10^{-5}	0.145
N	3.55×10^{-3}	42.7
O	2.71×10^{-4}	0.401
Ne	3.83×10^{-4}	3.19
Mg	1.21×10^{-4}	3.18
Si	1.13×10^{-4}	3.18
S	5.16×10^{-5}	2.41
Fe	1.01×10^{-4}	3.2