HDE 245059: A WEAK-LINED T TAURI BINARY REVEALED BY CHANDRA AND KECK

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Received 2008 September 16; accepted 2009 February 21; published 2009 May 4

ABSTRACT

We present the Chandra High Energy Transmission Grating Spectrometer and Keck observations of HDE 245059, a young weak-lined T Tauri star (WTTS), member of the pre-main-sequence group in the λ Orionis Cluster. Our high spatial resolution, near-infrared observations with Keck reveal that HDE 245059 is in fact a binary separated by 0.87′′, probably composed of two WTTS based on their color indices. Based on this new information we have obtained an estimate of the masses of the binary components: ≃3 M⊙ and ≃2.5 M⊙ for the north and south components, respectively. We have also estimated the age of the system to be ≃2–3 Myr. We detect both components of the binary in the zeroth-order Chandra image and in the grating spectra. The light curves show X-ray variability of both sources and in particular a flaring event in the weaker southern component. The spectra of both stars show similar features: a combination of cool and hot plasma as demonstrated by several iron lines from Fe xvii to Fe xxv and a strong bremsstrahlung continuum at short wavelengths. We have fitted the combined grating and zeroth-order spectrum (considering the contribution of both stars) in XSPEC. The coronal abundances and emission measure distribution for the binary have been obtained using different methods, including a continuous emission measure distribution and a multi-temperature approximation. In all cases we have found that the emission is dominated by plasma between ~8 and ~15 MK, a soft component at ~4 MK and a hard component at ~50 MK are also detected. The value of the hydrogen column density was low, N_H ≃ 8 × 10^{19} cm^{-2}, likely due to the clearing of the inner region of the λ Orionis cloud, where HDE 245059 is located. The abundance pattern shows an inverse first ionization potential effect for all elements from O to Fe, the only exception being Ca. To obtain the properties of the binary components, a 3-T model was fitted to the individual zeroth-order spectra using the abundances derived for the binary. We have also obtained several line fluxes from the grating spectra. The fits to the triplets show no evidence of high densities. In conclusion, the X-ray properties of the weak-lined T Tau binary HDE 245059 are similar to those generally observed in other weak-lined T Tau stars. Although its accretion history may have been affected by the clearing of the interstellar material around λ Ori, its coronal properties appear to not have been strongly modified.

Key words: stars: abundances – stars: coronae – stars: individual (HDE 245059) – stars: pre-main sequence – X-rays: stars

1. INTRODUCTION

T Tauri stars (TTS) are optically revealed pre-main-sequence stars (PMS) of low mass (M⋆ ~ 0.2–3 M⊙), whose interiors are fully convective and powered principally by gravitational contraction rather than by nuclear reactions. Low-mass PMS stars are classified optically in two types: classical T Tauri stars (CTTS) and weak-lined T Tauri stars (WTTS). The CTTS present strong Hα emission lines, a signature of accretion, and infrared excess, revealing a dusty circumstellar disk. On the other hand, WTTS present weaker Hα emission lines and little or no infrared excess, which is generally interpreted as a sign that active accretion has significantly decreased and the disk has become optically thin. PMS stars are magnetically active and rotate slowly during the early stages of their evolution and spin up as they contract to the main sequence (Stauffer & Hartmann 1986). Recent evidence suggests that there is also a population of low-mass PMS stars (0.3 ≤ M/M⊙ ≤ 1) that seems to contract toward the zero-age main sequence (ZAMS) at constant angular velocity during the first 3–5 Myr after they begin their evolution down the convective tracks (Rebull et al. 2004), indicating there should be a mechanism extracting angular momentum in these PMS objects. In CTTS the presence of disk and magnetic fields is believed to keep the rotation rate low, while the short rotational period in WTTS may be due to the dispersal of the circumstellar disk. But observational evidence has been sometimes confusing and the relation between accretion and angular momentum loss cannot be assured (Bouvier 2007).

Both types of stars are strong X-ray emitters that were first detected with the Einstein satellite, e.g., Feigelson & De Campli (1981) and subsequent observations with ROSAT (e.g., Feigelson et al. 1993; Neuhauser et al. 1995). Spectral measurements of X-rays from YSOs reveal emission from the continuum and lines from an optically thin plasma. Most of the TTS show variability in X-rays with timescales of minutes to days and can present strong flares.

X-ray spectroscopy of CTTS has shown some evidence that their X-ray emission could be due, at least in part, to accretion shocks on the stellar photosphere (Kastner et al. 2002; Stelzer & Schmitt 2004; Schmitt et al. 2005; Günther et al. 2006;
Argiroffi et al. (2007), although some CTTS do not support this mechanism. Their X-ray emission is believed to be coronal (Audard et al. 2005; Güdel & Telleschi 2007; Smith et al. 2005). An X-ray soft excess in CTTS is, however, reported compared with WTTS (Telleschi et al. 2007a). X-rays in WTTS are thought to originate only from magnetic activity similar to main-sequence magnetically active stars, albeit at much higher levels.

The low level of accretion in WTTS makes them the best-suited objects to study the magnetic activity in PMS stars, and the impact of stellar flares and X-rays onto their optically thin disks and their planets (Lammer et al. 2003, 2006; Smith & Scalo 2007).

WTTS show strong X-ray and nonthermal radio emission (Skinner 1993; Feigelson & Montmerle 1999). Compared to zero-age main-sequence stars, their X-ray luminosities are very high ($10^{28.5–31}$ erg s$^{-1}$), but they typically show $L_X/L_{bol} \approx 10^{-4}$. WTTS display very high coronal temperatures (Skinner et al. 1997; Tsuboi et al. 1998), X-ray flares with temperatures of a few tens of MK are frequently seen, e.g., Tsuboi et al. (1997; Tsuboi et al. 1998), although some CTTS do not support the same area of the Hertzsprung–Russell diagram; why are they getting improved diagnostics of the plasma properties.

CTTS and WTTS show similar ages and are found in the region which is believed to be the remnant of a supernova that exploded about 1–2 Myr ago. This explosion might have cleared the region and attempted to deduce its history. According to the authors, about 6 Myr ago the star formation process started in the most massive clouds of the region giving birth to several OB stars. This process increased gradually until approximately 1 Myr ago when a supernova exploded disrupting the central region and decreasing the star formation rate, yet not stopping it completely.

Our target (λ Ori X-1) was discovered in the X-rays with the Einstein Observatory during observations of the region centered at λ Ori cluster or Collinder 69. The photometric and astrometric study of the region shows evidence that our X-ray source is in fact member of the association. HDE 245059 shows a strong absorption in the Li (6707 Å) line, an indicator of youth (Alcalá et al. 2000). Based on comparison with evolutionary model isochrones, Stone & Taam (1985) estimated a mass and age of $M = 2–3 M_\odot$ and $t \sim 1–4$ Myr. More recent isochrones, e.g., those by Siess et al. (2000), however, might change the above estimates (see below, Section 5.1). Skinner et al. (1991) obtained an upper limit estimate for the disk mass around HDE 245059 of 0.32 $M_\odot$ based on the 1.1 mm continuum emission. Padgett (1996) obtained the effective temperature of HDE 245059, $T_{eff} = 4140 \pm 110$ K, and an estimate of the photospheric iron abundance, [Fe/H]$= -0.07 \pm 0.13$. Our target is a fast rotator ($v sin i \sim 25$ km s$^{-1}$), which in general is a sign of stellar youth or binaries of spectral types G and K (Fekel 1997). The studies of Fekel (1997) in the optical, and Alcalá et al. (2000) in the X-ray did not find evidence of radial velocity variability, an indication that HDE 245059 is not a spectroscopic binary. However, our high spatial resolution near-infrared observations with Keck indicate that it is, in fact, a spatially separated binary (see Section 3.1).

3. OBSERVATIONS

3.1. Near-infrared

On 2003 December 13, we observed HDE 245059 with NIRSPEC (McLean et al. 2000) installed behind the adaptive optics system (Wizinowich et al. 2000) on the 10m Keck II telescope. The imaging camera within NIRSPEC offers a pixel scale of 0′′0168 ± 0′′0001 and an absolute orientation of 1′1 ± 0′08 as determined from observations of calibration binaries and of a reference field in the Orion Trapezium. HDE 245059 was used as the adaptive optics guide star with the wave front sensor running at a frequency of 488Hz, resulting in good correction (Strehl ratios of 43 and 19% at 2.2 and 1.6 μm, respectively). We acquired images of the system with the broadband $K$ ($\lambda_0 = 2.20 \mu m$, $\Delta \lambda = 0.39 \mu m$) and NIRSPEC-5 ($\lambda_0 = 1.61 \mu m$, $\Delta \lambda = 0.40 \mu m$, a close analog to the usual $H$ filter) as well as with the narrowband Brγ filter ($\lambda_0 = 2.165 \mu m$, $\Delta \lambda = 0.02 \mu m$). In each filter, a series of short exposures were co-added at four successive positions on the detector. The total integration times were 40s, 4s, and 20s with the $K$, $H$, and Brγ filters, respectively. For each filter, the four independent images were medianed to create a sky that was subtracted from each image. The images were then realigned and averaged to produce the final images. Relative astrometry and photometry was obtained using...
Figure 1. Near-infrared Keck adaptive optics images of HDE 245059 in H, K, and Brγ (2.165 μm) bands. The image is in square-root scale; north is toward the top and east is toward the left.

the DAOPHOT package. The astrometric results from all three filters were finally averaged to reduce random uncertainties.

The near-infrared images resolved HDE 245059 into a binary. Figure 1 shows the near-infrared Keck adaptive optics images of HDE 245059 with the three filters. The northern component is brighter in all images. The projected separation and uncertainty is 0′.866 ± 0.005 and the position angle, measured east from north is 150′.0 ± 1′.0. The final astrometric uncertainties are dominated by the absolute calibration uncertainties of the detector. We measured magnitude differences of 0.98 mag, 0.88 mag, and 0.86 mag with the H, K, and Brγ filters respectively (with typical uncertainties of 0.03 mag). These differences suggest that both components have similar broadband colors.

3.2. X-rays

X-ray observations were performed using the High-Energy Transmission Gratings (HETG) in combination with the Advanced CCD Imaging Spectrometer (ACIS-S), on board of the Chandra X-Ray Observatory (CXO). We obtained a total exposure time of 93 ks scheduled in three epochs: 2005 December 30, 2006 January 7, and 2006 January 13, (Observation identification numbers 6241, 7253, and 5420, respectively). The short time interval between the observations allowed similar roll angles: 308:5 for the first two and 294:8 for the last one.

Both components of the binary were detected in the zeroth-order image. The binary orientation was close to the dispersion direction of the Chandra MEG arm. Choosing the origin of the wavelength system between the two stars we were able to separate them in the grating spectra despite the small separation.

4. CHANDRA DATA REDUCTION AND ANALYSIS

The data of the HETGS observations were reduced from level 1 event files with the Chandra Interaction Analysis of Observations software, CIAO 3.4, using the calibration database, CALDB 3.3.0.1, and following standard procedures to obtain a type 2 event file. We removed streak events that significantly affect ACIS-S4 (CCD ID=8).

4.1. Zeroth-Order Images

For the zeroth-order images, we used the subpixel event repositionary (SER) algorithm in order to improve spatial resolution (Tsunemi et al. 2001; Li et al. 2003, 2004). When an X-ray photon hits the detector, the charge cloud created can either be spread into neighboring pixels (called split pixel event) or remains in a single pixel (called single pixel event). Positions are determined with higher accuracy in the case of a split pixel event, however these events represent only a small fraction of the total events. The SER technique uses both single pixel events and 2 pixel split events to increase the statistics. When applied to the ACIS observations the SER technique reduces the uncertainties in the determination of the photon-impact position improving the spatial resolution. The improvement in FWHM is typically between 40% and 70%.

The zeroth-order images of HDE 245059 for each observation epoch are displayed in Figure 2. A flare from the south component is visible in the first observation epoch (first panel). The summed zeroth-order image over all the observation runs, Figure 2 last panel, clearly shows the two components, the north component being on average the brighter one.

4.2. Light Curves

Figure 3 shows the light curves of the zeroth-order data for the three observation epochs. The light curves were extracted from the data treated with the SER algorithm using a 2′.1 radius for the binary and 0′.4 radius for each component, thus, the sum of the light curves of both components do not match the binary light curve. During the first observation epoch, a flare is detected from the south star, starting approximately 6 ks after the beginning of the observation. The flare lasted for nearly 6 ks, peaking 1.5 ks after its start with 0.06 counts s⁻¹, roughly five times higher than the southern star average count rate for the first observation epoch.

We have also included the hardness ratio for the first observation epoch as an inserted figure in the light curve plot (Figure 3 top panel). The hardness ratio was calculated using the expression H/S, where the soft band (S) was taken in the range from 0.3 to 2 keV and the hard band (H) was taken in the range from 2 to 10 keV.

4.3. Spectra

4.3.1. Binary Components

Thanks to the spatial resolution of Chandra we have separated the components of the HDE 245059 binary in the zeroth-order spectrum. The spectrum was extracted after merging the event files from the three observation epochs following standard CIAO procedures, using a circular region of radius 0′.4 for each star. The background was extracted from an annular region with radii of 4′.6 and 21′. We have considered events within the range 0.2–7 keV, where most of the signal is concentrated. We have obtained the spectra for the quiescent state for each component.

In Figure 4 we have plotted the spectra and overlaid the best-fit model for each star. The northern star spectrum shows a higher signal with respect to the southern companion, which is consistent with the results from the zeroth-order image.

We have fitted the individual spectra of the binary components obtained from the zeroth-order data (see Table 1) using XSPEC version 11 (Arnaud 1996), and a discrete emission measure distribution (EMD). The hydrogen column density and abundances were fixed to the zeroth-order plus grating best-fit values (discussed in Section 4.3.3). For the north component we have fitted a 3-T plasma, with temperatures in the range between 6 MK and 40 MK. The emission is dominated by the softer plasma with temperatures in the range between 6 and 13 MK. The average temperature was defined as log $T_{av} = (\Sigma_i \log T_i \times EM_i)/EM_{total}$. 

![Figure 2. Zeroth-order X-ray image of HDE 245059 in square-root scale for the three observation epochs. A flare is visible in the south component during the first epoch. At the far right, the average image obtained by summing the three observations.](Image 2005/12/30 2006/01/07 2006/01/13)
leading to $T_{av} = 11.3$ MK. The upper limit for the component at 40 MK was not well constrained.

For the southern star, we could not fit the soft component at 6 MK that was obtained for northern star. We have found a 2-$T$ plasma with temperatures 8 MK and 34 MK, the emission is dominated by the plasma at 8 MK. Again in this case, the upper limit for the highest temperature (34 MK) was not well constrained. The average temperature was 12.2 MK, slightly higher than the average of the northern star.

We remark that the sum of the emission measures, as well as the luminosity, obtained for both components of the binary does not match the value of the total emission measure found in our
fits to the combined spectrum of the binary (see Section 4.3.3) due to the different extraction radii used for the binary and their components.

4.3.2. Flare

To analyze the spectrum from the southern star during the flare we have extracted only the zeroth-order spectrum, since we do not have enough signal in the gratings. We have fitted a multi-temperature (multi-T) model leaving the photoelectric absorption component, abundances, and temperatures fixed to the values from the best fit to the quiescent state of the southern star. We have then added an extra temperature component for which we have left only the emission measure and temperature free to vary. We could not add more than one temperature component to our model, probably due to the low signal obtained.

Our fit shows that the flare emission is dominated by a plasma at $\sim 30$ MK (see Table 2). The luminosity during the flare increases to $7.6 \times 10^{30}$ erg s$^{-1}$, which is a factor of 5 higher than the luminosity of the quiescent state. The high temperature found during the flare is also present in the quiescent state, indicating that the variable component during the flare originates mainly in the hotter part of the emission measure distribution.

4.3.3. HDE 245059 Binary

The combined zeroth-order CCD spectrum of HDE 245059 was extracted after merging the event files from the three observation epochs following standard CIAO procedures. This was possible thanks to the similar pointing and setup between the observations. We have used a circular region with 3.9 radius. The background was extracted from an annular region with radii of 4$\prime$.6 and 21$\prime$. We considered events at energies within the range 0.2–7 keV.

The grating spectra of the HDE 245059 binary were extracted for both the HEG (High Energy Grating, 0.8–10 keV) and MEG (Medium Energy Grating, 0.4–5 keV) orders $\pm 1$. We have selected the wavelength range between 2.8–25 Â and 1.8–17.3 Â for MEG and HEG, respectively. The spectra were binned by a factor of 3 in wavelength, in particular to sum the contribution of both stars in the MEG spectra (since both stars are aligned with the dispersion direction). The respective spectral responses were generated using standard CIAO tools. The spectra of all the observation epochs were then merged using the CIAO procedure merge_all. In Figure 5, we show the binary grating spectrum for MEG and HEG first orders. We have labeled some important emission lines.

We have analyzed the spectrum of the binary HDE 245059 during the quiescent state using the combination of the zeroth-order spectrum plus the grating spectrum from HEG order 1, and MEG order 1. For the fits we have used three methods: a multi-T component model as a discretization of the EMD, a continuous EMD form Chebyshev polynomials, and a continuous EMD model of the average EMD.

In Table 3 we show the best fit parameters for the quiescent state. We have used the combination of the zeroth-order data plus the gratings HEG $\pm 1$ and MEG $\pm 1$. All the values are displayed with their respective errors calculated with $\Delta C = 1$.

### Table 2

| Parameter | Value |
|-----------|-------|
| $T$ (MK)  | 30.4$^{+0.5}_{-0.5}$ |
| EM (10$^{34}$ cm$^{-3}$) | 1.3$^{+0.3}_{-0.2}$ |
| $N_H$ (10$^{20}$ cm$^{-2}$) | 7.7 |
| Flux (10$^{-13}$ erg cm$^{-2}$ s$^{-1}$) | 3.9 |
| $L_X$ (10$^{30}$ erg s$^{-1}$) | 7.6 |
| C-statistics | 8 |
| dof | 11 |

**Note.** The fit was obtained fixing all the parameters: temperatures, emission measures, abundances, and hydrogen column density to the values obtained from the best fit to the quiescent state and adding an extra temperature component that was set free to vary.

### Table 3

| Parameter | Quiescent |
|-----------|-----------|
| $T_1$ (MK) | 3.9 $\pm$ 0.3 |
| $T_2$ (MK) | 8.1 $\pm$ 0.3 |
| $T_3$ (MK) | 15.6$^{+0.5}_{-0.5}$ |
| $T_4$ (MK) | 50.2$^{+0.5}_{-0.5}$ |
| $T_w$ (MK) | 10.7 |
| EM$_1$ (10$^{34}$ cm$^{-3}$) | 1.1 $\pm$ 0.2 |
| EM$_2$ (10$^{34}$ cm$^{-3}$) | 2.9 $\pm$ 0.3 |
| EM$_3$ (10$^{34}$ cm$^{-3}$) | 2.7$^{+0.4}_{-0.3}$ |
| EM$_4$ (10$^{34}$ cm$^{-3}$) | 0.6$^{+0.5}_{-0.3}$ |
| EM$_{total}$ (10$^{34}$ cm$^{-3}$) | 7.29 |
| $N_H$ (10$^{19}$ cm$^{-2}$) | 7.7$^{+2.6}_{-2.0}$ |
| O | 0.30$^{+0.05}_{-0.04}$ |
| Ne | 0.71 $\pm$ 0.06 |
| Mg | 0.21 $\pm$ 0.03 |
| Al | 0.34$^{+0.06}_{-0.02}$ |
| Si | 0.18 $\pm$ 0.02 |
| S | 0.14$^{+0.05}_{-0.04}$ |
| Ar | 0.46 $\pm$ 0.3 |
| Ca | 0.58 $\pm$ 0.3 |
| Fe | 0.23 $\pm$ 0.02 |
| Ni | $\leq$ Fe |
| Flux (10$^{-13}$ erg cm$^{-2}$ s$^{-1}$) | 5.2 |
| $L_X$ (10$^{31}$ erg s$^{-1}$) | 1.0 |
| C-statistics | 4148 |
| dof | 3708 |

**Notes.** Method 1 uses a discretization of the EMD by a multi-T model (see Section 4.3.4 for details.) We present here the best-fit 4-T model of the average HDE 245059 binary for the quiescent state. We have used the combination of the zeroth-order data plus the gratings HEG $\pm 1$ and MEG $\pm 1$. Abundances are given with respect to the solar photospheric values (Grevesse & Sauval 1998). All errors are calculated with $\Delta C = 1$.
was defined as $\log T_{av} = (\Sigma \log T_i \times EM_i)/EM_{total}$, leading to $T_{av} = 10.7$ MK. The value of the hydrogen column is very low, $N_H = 8 \times 10^{19}$ cm$^{-2}$, corresponding to $A_V = 0.04$ mag, which is consistent with the Two Micron All Sky Survey (2MASS) colors of the binary ($J - K = 0.6$) and with photospheric colors of early K-type stars. We remark that the results obtained from the fit to the quiescent state are not different from the results obtained from fitting the total average spectrum (considering also the flare).

The best-fit model overlaid to the HEG ±1 and MEG ±1 data for the quiescent state are shown in Figure 5. The brightest line detected is Ne xi Lyα at 12.13 Å. Significant emission also comes from O viii Lyα at 18.97 Å, Ne x Lyβ at 10.23 Å. Interestingly there is no detection of O vii or N vii despite the low $N_H$. Lines from highly ionized states of Fe xvii to Fe xxiv confirm the presence of a wide range of plasma temperatures revealed by our fits.

4.3.5. Method 2: Continuous EMD from Chebyshev Polynomials

The differential EMD $\varphi(T)$ is given by

$$\varphi(T) = n_H n_e dV/dT \text{ (cm}^{-3} \text{K}^{-1}),$$

(1)

where the total EM is given by $EM_{tot} = \int \varphi(T) T \Delta \log T = \int \varphi(T) T d(\ln T)$. A graphical representation of the EMD independent of the grid bin size ($\Delta \log T$) is given by $EMD(T)/\Delta \log T$.

This method assumes that the shape of $\varphi(T)$ can be approximated by the exponential of a polynomial given by $\varphi(T) = \alpha \omega(T)$, where $\alpha$ is a normalization constant and $\omega(T)$ is a polynomial function of the temperature, which we have chosen to be a Chebyshev polynomial (see Lemen et al. 1989; Audard et al. 2004).

Our model uses a grid of temperatures in the range $\log T(K) = 8–10$ with $\Delta \log T = 0.2$ dex for a polynomial degree of $n = 8$ which gives the optimal fit. Coronal abundances and the photoelectric absorption were left free to vary. The results obtained with this method are displayed in Table 4.

4.3.6. Method 3: Continuous EMD Approximated by Two Power Laws

This method is based on a continuous EMD described by two power laws; one at low temperatures with slope $\alpha$, and one at high temperatures with slope $\beta$ (see Telleschi et al. 2007b). The EMD peaks at the temperature $T_0$ which also represents the limit between the two regimes.

$$Q(T) = \begin{cases} EM_0(T/T_0)^\alpha & \text{for } T \leq T_0 \\ EM_0(T/T_0)^\beta & \text{for } T > T_0 \end{cases}$$

The normalization parameter is defined as the EM in the temperature bin at $T_0$. The free parameters are: $T_0$, EM$_0$, $\alpha$, $\beta$, $N_H$, and the elemental abundances. We have used 2 approximations; first leaving $\alpha$ and $\beta$ free to vary, and after fixing the value of $\alpha = 2$ leaving $\beta$ free to vary. The value $\alpha = 2$ is usually found in magnetically active main-sequence and PMS stars. $\Delta \log T = 0.1$ dex was set in both cases. The results obtained with this method are displayed in Table 5.

In Figure 6 we have plotted the EMD of the binary obtained by the different methods applied. In order to compare them we...
Table 4
Best Fit to the Quiescent Spectrum of the HDE 245059 Binary Using Method 2

| Parameter | Value |
|-----------|-------|
| EM_{total} (10^{54} \text{ cm}^{-3}) | 7.3 |
| N_{He} (10^{19} \text{ cm}^{-3}) | 6.9_{-3}^{+2} |
| O | 3.4 \pm 0.03 |
| Ne | 0.69 \pm 0.06 |
| Mg | 0.21 \pm 0.02 |
| Al | 0.33 \pm 0.2 |
| Si | 0.18 \pm 0.02 |
| S | 0.15_{-0.04}^{+0.06} |
| Ar | 0.46 \pm 0.3 |
| Ca | 0.51 \pm 0.3 |
| Fe | 0.23 \pm 0.02 |
| Ni | = Fe |
| C-statistics | 4161 |
| dof | 3708 |

Notes. Method 2 is based on a continuous EMD obtained from Chebyshev polynomials, in this case we have used a degree of 8 (see Section 4.3.5). This method has been applied to the quiescent state spectrum of the binary. Abundances are given with respect to the solar photospheric values (Grevesse & Sauval 1998). Errors are calculated with $\Delta C=1$.

Table 5
Best Fit to the Quiescent Spectrum of the HDE 245059 Binary Using Method 3

| Parameter | $\alpha$ Fixed | $\alpha, \beta$ Free |
|-----------|----------------|-------------------|
| $\alpha$ | $\geq$2.0 | 2.4 \pm 0.4 |
| $\beta$ | $-1.5 \pm 0.09$ | $-1.5 \pm 0.09$ |
| log $T_0$ | 7.0 \pm 0.01 | 6.9_{-0.02}^{+0.03} |
| EM_{total} (10^{54} \text{ cm}^{-3}) | 7.49 | 7.31 |
| N_{He} (10^{19} \text{ cm}^{-2}) | 8.7 \pm 2.5 | 8.0_{-2.5}^{+2.5} |
| O | 0.28 \pm 0.04 | 0.30_{-0.04}^{+0.04} |
| Ne | 0.68_{-0.06}^{+0.05} | 0.69_{-0.05}^{+0.06} |
| Mg | 0.21_{-0.02}^{+0.03} | 0.20_{-0.02}^{+0.03} |
| Al | 0.35 \pm 0.2 | 0.34 \pm 0.2 |
| Si | 0.18 \pm 0.02 | 0.17 \pm 0.02 |
| S | 0.15_{-0.04}^{+0.05} | 0.15_{-0.04}^{+0.05} |
| Ar | 0.43 \pm 0.3 | 0.44 \pm 0.3 |
| Ca | 0.45 \pm 0.3 | 0.46 \pm 0.3 |
| Fe | 0.23 \pm 0.02 | 0.22 \pm 0.02 |
| Ni | = Fe | = Fe |
| C-statistics | 4168 | 4167 |
| dof | 3714 | 3713 |

Notes. Method 3 is based on a continuous EMD described by two power laws. It has been applied to the quiescent spectrum of the binary. In the first case we have fixed one of them, while in the second case we have left both the power-law indices free to vary (see Section 4.3.6 for details). Abundances are given with respect to the solar photospheric values (Grevesse & Sauval 1998). Errors are calculated with $\Delta C=1$.

have used the quantity EMD($T$)/$\Delta$log$T$ which is independent of the bin size. The total volume emission measure obtained from the different methods are similar: 7.3 for method 1, 7.1 for method 2, 7.5 for method 3 with $\alpha$ fixed and $\beta$ free, and 7.3 for method 3 with $\alpha$ and $\beta$ free (all values are in units of $10^{54} \text{ cm}^{-3}$).

4.4. Fitting

4.4.1. Electron Densities

We have obtained the fluxes of the density sensitive He-like triplets Si xii, Mg xi, and Ne ix from the binary grating spectrum (HEG and MEG first order). The first step was to fit the continuum to get an estimate of the plasma temperature. We used a bremsstrahlung model, taking the spectrum without the contribution of the bright lines and considering the wavelength range between 1.2 Å and 40 Å. We have obtained a plasma temperature of 12.4 $\pm$ 0.3K close to the average temperature found in our previous best fit of the grating plus zeroth-order spectrum. To fit the triplet lines (resonance ($r$), intercombination ($i$), and forbidden ($f$)) we used the combination of delta functions for the line profiles and the above mentioned bremsstrahlung model for the continuum. We have fixed the continuum parameters and fitted the triplets only in the wavelength range of interest. The only free parameters in our fits were the line fluxes, since the wavelength of each line was fixed. Since the Ne ix triplet is blended with Fe xix, we added a delta profile to consider this blend. The results are summarized in Table 6. In Figure 7, we have plotted the three triplets for the MEG first-order spectrum including the delta profiles used to fit the lines. Based on theoretical models (Porquet et al. 2001), using the $R = f/i$ ratio and the temperature of the emitting plasma we have obtained an estimate of the plasma electron density. We have calculated the densities using confidence levels of 68% and 90% (see Table 7). For the 68% confidence level, we have obtained $n_e = (5 \pm 5) \times 10^{12} \text{ cm}^{-3}$ from the Ne ix triplet, $n_e = 1.3_{-0.5}^{+2.0} \times 10^{13} \text{ cm}^{-3}$ from Mg xi, and $n_e < 5 \times 10^{13} \text{ cm}^{-3}$ from Si xii, which is consistent with the low-density plasma. For the 90% confidence level, we have obtained $n_e \leq 2.0 \times 10^{12} \text{ cm}^{-3}$ from the Ne ix triplet, $n_e = 1.5_{-0.8}^{+1.9} \times 10^{13} \text{ cm}^{-3}$ from Mg xi, and $n_e < 3 \times 10^{14} \text{ cm}^{-3}$ from Si xii. Therefore, we prefer to err on the safe side and conclude that there is no evidence of high densities in HDE 245059.
Table 6
Line Fluxes for the Binary HDE 245059

| Ion  | \(\lambda\) (Å) | Flux \(\times 10^{-7}\) photons cm\(^{-2}\) s\(^{-1}\) |
|------|-----------------|----------------------------------|
| Si xii(r) | 6.65 | 0.5 ± 0.1 |
| Si xii(i) | 6.68 | 0.1 ± 0.04 |
| Si xii(f) | 6.74 | 0.3 ± 0.1 |
| Mg xii(r) | 9.17 | 0.3 ± 0.1 |
| Mg xii(i) | 9.23 | 0.2 ± 0.1 |
| Mg xii(f) | 9.31 | 0.3 ± 0.1 |
| Ne xiii(r) | 13.45 | 2.7 ± 0.3 |
| Ne xiii(i) | 13.55 | 0.9 ± 0.2 |
| Ne xiii(f) | 13.70 | 1.7 ± 0.3 |
| Fe xix | 13.52 | 1.4 ± 0.3 |

Notes. Single line fluxes and He-like triplets obtained from the model of the MEG±1 and HEG±1 data using the combination of a bremsstrahlung model for the continuum and delta profiles for the lines. For the O vii triplet we include the flux estimate at two confidence levels; 68% and 90%. In the case of Ne ix we have also added a delta profile for Fe xix which is blended with the Ne line. The fluxes are not corrected for the absorption column density.

Table 7
Line-Flux Ratios and Derived Electron Densities for the HDE 245059 Binary

| Triplet | \(R\) | \(n_e\) \(\times 10^{13}\) cm\(^{-3}\) | \(R\) | \(n_e\) \(\times 10^{13}\) cm\(^{-3}\) |
|---------|-------|-----------------|-------|-----------------|
| Ne ix  | 2.0 ± 0.8 | 5 ± 5 \times 10^{11} | 2.0 ± 1.1 | < 2 \times 10^{12} |
| Mg xii | 1.4 ± 0.6 | 1.0 \times 10^{13} | 1.4 ± 1.0 | 1.6 \times 10^{13} |
| Si xiii | 2.3 ± 0.9 | < 5 \times 10^{13} | 2.3 ± 1.6 | < 3 \times 10^{14} |

Notes. Line flux ratios \(R = f_1 / f_2\) and electron densities derived from the He-like triplets. Calculations were made for the grating spectrum of the binary (HEG and MEG first order) at two confidence levels, 68% and 90%. See Section 4.4.1 for discussion.

4.4.2. Lines Fluxes from Each Binary Component

We have also attempted to obtain individual fluxes from several lines for each component of the binary. We have used only the first-order spectra of MEG because of the higher signal to noise, and because the binary was aligned along the MEG dispersion direction, allowing us to disentangle the two components in wavelength space. The spectrum was re-extracted using a bin size of 0.015 Å. To fit the single lines we used the method described in Section 4.4.1; a combination of a delta function for the line profile and the bremsstrahlung model for the continuum. The fits to the MEG+1 and MEG−1 data were made simultaneously because the shift of the lines will occur in opposite directions from the origin of the reference wavelength. For each line we considered only the instrumental profile, therefore we had four delta profiles: two for the MEG+1, northern and southern stars and the same for the MEG−1. From the grating equation, we calculated the shift of the lines. The line shifts were smaller than the line-spread function FWHM, with a typical separation of 17 mÅ. To fit the lines, we fixed the energy at which they were expected to be found, leaving only the fluxes free to vary. Besides, the fluxes from each star were linked for MEG+1 and MEG−1. The fits thus considered two free parameters: the flux of the line from each star. The calculations were made whenever the signal for a given element
Figure 8. Plot shows the Mg xii Lyα, Ne x Lyα, Ne x Lyβ, and O vii Lyα lines for the grating data. In solid line the MEG-1 and in dashed line the MEG+1. The line were modeled with a bremsstrahlung plus a Gaussian model taking into account the contribution of both stars. We considered the profiles to be purely instrumental.

Table 8
Line Fluxes for HDE 245059 Binary Components

| Ion      | λ (Å) | Flux (10^-5 photons cm^-2 s^-1) |
|----------|-------|---------------------------------|
|          |       | North                          | South                         |
| Mg xii   | 8.42  | 0.5 ± 0.1                      | 0.1 ± 0.1                     |
| Ne x Lyα | 12.13 | 3.7 ± 0.4                      | 2.8 ± 0.4                     |
| Ne x Lyβ | 10.24 | 0.5 ± 0.1                      | 0.2 ± 0.1                     |
| O vii Lyα| 18.97 | 7.4^{+1.1}_{-1.1}              | 5.7^{+1.1}_{-1.1}             |

Notes. Single line flux obtained for each star of the binary from the model of the MEG±1 data using the combination of a bremsstrahlung model for the continuum and a delta function for the line profiles. The fluxes are not corrected for the absorption column density.

was high enough; we have then obtained fluxes for O vii Lyα, Ne x Lyα, Ne x Lyβ, and Mg xii Lyα. For the He-like triplets the signal was too low, thus we did not obtain fluxes for the single binary components. The results are displayed in Table 8; in Figure 8 we have plotted the line profiles for the full resolution grating MEG±1 data.

5. DISCUSSION

5.1. Environment and Binarity

The absence of a disk in the WTTS HDE 245059 members despite their young age might be closely related to the environment where this young binary has been formed. The evolution of the region around λ Ori has been discussed in detail (Dolan & Mathieu 1999, 2001, 2002; Barrado y Navascués et al. 2007). Dolan & Mathieu (1999, 2001, 2002) presented the hypothesis of a supernova explosion that cleared out the region about 1 Myr ago leaving a molecular ring. During the phase prior to the supernova explosion the stars in the cluster would have been confined in a small region and the circumstellar disks cleared away by photoevaporation. This hypothesis is supported by the small fraction of CTTS in the region, ~7% (Dolan & Mathieu 1999), which is low when compared with clusters with similar properties. Barrado y Navascués et al. (2007) have studied the members of the λ Ori with the Spitzer satellite, finding a 31% of members with disks in λ Ori, but only 14% with thick disks. According to this study, the presence of CTTS near the center of the cluster would suggest that massive stars and the supernova explosion had no major effect on the disks, or that they have been formed after the explosion. Recent high-resolution optical spectroscopy of the λ Ori cluster (Sacco et al. 2008) has given a fraction of stars with disks of 28%, higher than the previous studies. Our new estimates of the properties of the HDE 245059 binary (see Section 5.2) give an age of ≈ 2–3 Myr: at this age the binary would have experienced the supernova explosion, according to the Dolan & Mathieu (1999, 2001, 2002) hypothesis. Another aspect to be considered is the influence of binarity in the disk truncation. This hypothesis has been discussed by Kraus et al. (2008), who presented recent results showing that several of the young stars without disks in a survey of nearby star-forming regions are close binaries.
5.2. Stellar Properties

The discovery of the binarity of HD 245059 prompts us to re-evaluate the stellar properties of the system. The few physical properties; mass, age, spectral type, and effective temperature were previously obtained under the assumption of a single star (Padgett 1996; Stone & Taam 1985). Our near-infrared and X-ray data have been the first to separate it into a binary. The question that arises immediately is how different the properties of the HDE 245059 members are. The magnitude differences from the near-infrared images in the H, K, and Brγ bands suggest that both components have similar colors, but the northern star is brighter in both near-infrared and X-ray images, which might indicate that is the more massive of the system. Throughout this analysis, we assume a distance of 400 pc to the system. We further assume that the flux we receive from each component can be entirely attributed to the stellar photosphere, without contribution from accretion for instance, in line with the WTTS status of the system.

In a first approach, the absolute near-infrared magnitudes of each component can be used to estimate its main properties (mass and age). Combining the unresolved 2MASS photometry of the system with our new H- and K-band flux ratios, we determine absolute magnitudes of $M_H = -0.07$ and $M_K = -0.20$ for the primary and $M_H = +0.91$ and $M_K = +0.68$ for the secondary.¹⁰ Such absolute magnitudes are too bright for solar-like stars even at ages as young as 1 Myr, based on the stellar evolutionary models of Baraffe et al. (1998) and Siess et al. (2000). To explore higher-mass regimes, we adopt the models of Siess et al. (2000) which extend up to 7 $M_\odot$. Based on this model, for ages of 4 Myr or more, only B-type stars reach the observed brightness of HD 245059 north and south. At 3 Myr, at least the primary would have to be a B star. Since this can be confidently excluded from the spectral analysis of Padgett (1996), we conclude that the system is no older than 2 Myr. Assuming stellar ages in the 1–2 Myr range (since star formation appears to have ceased about 1 Myr ago; see, e.g., Dolan & Mathieu 2001), a primary of 2.5–3.5 $M_\odot$ and a secondary of 2–3 $M_\odot$ would match the observed near-infrared magnitudes of the two components.

To improve on this estimate and take advantage of a broader dataset, we perform a fit to the optical and infrared spectral energy distribution (SED) of the system. For this purpose, we use the unresolved $UBV$ photometry from Stone & Taam (1985), the unresolved J magnitude from 2MASS, the spatially resolved photometry derived above and the 3.6, 4.8, 5.6, and 8 μm unresolved IRAC photometry determined from archival images and using default recipes for aperture correction around point sources. This represents a total of 12 independent measurements. We used a grid of NextGen stellar spectra from Baraffe et al. (1998) with log $g = 4.0$ (our results are largely insensitive to the assumed surface gravity). We used five free parameters in our model: the stellar effective temperatures $T_{\text{eff}}(N)$ and $T_{\text{eff}}(S)$, the stellar radii $R_N$ and $R_S$, and the extinction $A_V$. To ensure that we did not miss the best possible solution, we conservatively allowed for wide ranges of initial guesses (4600–7600 K for $T_{\text{eff}}(N)$, 2400–7000 K for $T_{\text{eff}}(S)$, 3.5–6 $R_\odot$ for $R_N$, 2–9 $R_\odot$ for $R_S$ and 0–1.5 mag for $A_V$). In this procedure, we do not use information from evolutionary models as prior and only require that $T_{\text{eff}}(S) \leq T_{\text{eff}}(N)$. Overall, we tested about five million independent combinations of the five free parameters, estimating a reduced $\chi^2$ value for each model. We then used a Bayesian inference method to explore the parameter space: each model in the grid is assigned a probability $p = e^{-\chi^2/2}$, and one- and two-dimensional probability distributions for individual and pairs of free parameters are then produced by marginalizing the hypercube against the other dimension.

Using the mode of each one-dimensional probability distribution and defining a 68% confidence level interval around it, we infer $T_{\text{eff}}(N) = 5850^{+730}_{-250}$ K, $T_{\text{eff}}(S) = 3460^{+1290}_{-760}$ K, $R_N = 4.94^{+0.26}_{-0.27} R_\odot$, and $R_S = 4.27^{+1.64}_{-0.92} R_\odot$. However, as illustrated in Figure 9, there is substantial ambiguity between $T_{\text{eff}}(S)$ and $R_S$ due to the fact that we only have two measurements that directly constrain the secondary. A cool but large secondary star fits equally well the data as a warmer and more compact star. This correlation between the stellar parameters also explains the difference between the absolute best model (i.e., lowest $\chi^2$) and the most probable stellar parameters based on the one-dimensional probability distributions. Both estimates nonetheless agree within the uncertainty, although we prefer to use the two-dimensional probability distributions to estimate the stellar properties.

The final step in this analysis consists in overplotting the predictions of the Siess et al. (2000) evolutionary models. We note that both the stellar luminosity and radius are direct output of these models so this is a natural set of parameters to compare model and data. In Figure 9, we overplot the 1, 2, 3, and 5 Myr isochrones and readily conclude that the primary star is most likely ≈2 Myr old. Similar to the conclusion based solely on the near-infrared magnitudes, stellar ages beyond 3 Myr can be confidently excluded. While the best fit to the secondary suggests an age even younger than 1 Myr, the 2 Myr isochrone does intercept the 68% confidence level contour. Using 6000 K and 5 $R_\odot$ (equivalently, 29 $L_\odot$) for the primary, interpolation in the Siess et al. (2000) model yields a stellar mass of 2.7 $M_\odot$ and

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¹⁰ Note that extinction, if present in front of the system, would yield even higher absolute magnitudes.
an age of 2.7 Myr. From the extent of the 68% confidence level contour, we estimate uncertainties of 0.5 \( M_\odot \) and 1 Myr. Based on the 2.7 Myr best-fitting age, we further infer \( M_S = 2.3 - 2.4 \ M_\odot \).

While relatively large uncertainties remain due to the limited number of resolved photometric measurements of the system, we conclude that the stellar masses are \( \approx 3 \ M_\odot \) and \( \approx 2.5 \ M_\odot \) and the age of the system is \( \approx 3 \) Myr. High spatial resolution optical data, which are currently unavailable for the system, would greatly improve the accuracy on these parameters. Nonetheless, we consider that this is a significant improvement over the previous estimates that did not take into account the fact that the system is indeed a binary. As a final note regarding the stellar properties, we note that the age of HD 245059 is younger than the average age of other members of the \( \lambda \) Ori association but also consistent with that of the youngest systems in the associations.

5.3. Spectral X-ray Properties

The fits to the high-resolution grating spectroscopy data have revealed that both stars have similar spectral properties and emission measure distributions. Indeed, the spectra of the single components are consistent with the average spectrum of the binary. The similar temperatures of both stars allowed us to fit easily the grating spectra together.

We do not detect the oxygen triplet in HDE 245059, either in the average or in the single spectra, despite the low \( N_H \) value. We have estimated an upper limit flux for the O vii triplet (see Table 6) at two confidence levels: 68% and 90% for the average binary spectrum. This triplet is used as an electron density indicator in the cool plasma component, expected to be present in the spectra of accreting stars. On the other hand we do find a soft plasma component at 3.8 MK in the average spectrum: the He-like triplet of Ne xi was detected with low signal to noise and it was found to be blended with the Fe xvi line. We also detect emission from Fe xvii blended with other lines.

In order to determine the nature of our nondetection of the O vii triplet, we have fitted some single lines for the combined spectrum of the HDE 245059 binary: O vii Ly\( \alpha \), Ne ix, Ne x Ly\( \alpha \), and Fe xvii at 15 \( \AA \) (Table 6). We have compared the results with the observed line fluxes of three young active stars: 47 Cas B, EK Dra (Tellerschi et al. 2005) and AB Dor (Garcia-Alvarez et al. 2008). We have found the line fluxes of the HDE 245059 binary to be about a factor of 100 larger than the fluxes of the comparison stars. Using this ratio for the O vii resonance line at 90% confidence level, our upper limit for HDE 245059, less than \( 2 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\), remains close to what could have been expected based on the comparison stars. We conclude that the nondetection of the O vii triplet is probably due to a lack of sensitivity around 22 \( \AA \).

Observations of the Sun show that abundances are related to the first ionization potential (FIP) of the elements in such a way that elements with low FIP (\( \lesssim 10 \) eV) are overabundant in the solar corona when compared with the photosphere and high FIP elements (\( > 10 \) eV) have similar abundances in the corona and the photosphere (Feldman 1992). Observations of young, magnetically active stars show that the FIP effect is inverted with respect to the Sun; i.e., low FIP elements are underabundant in the stellar coronae relative to elements with high FIP (Brinkman et al. 2001; Audard et al. 2003).

Figure 10 shows the coronal abundances with respect to the solar photospheric values for our binary plotted against the FIP. The abundances follow the trend of an inverse FIP effect, except for the Ca abundance which has a higher value, but we recall that the uncertainty in Ca abundance from our results is also high.

A common problem found in the studies of the coronal element abundance is the lack of measurements of the stellar photospheric abundances, as they are difficult to obtain due to the large rotational velocity of magnetically active stars. Furthermore, good knowledge of the stellar parameters and atmospheric models is also needed. To sort out this problem, the stellar photospheric abundances are used as a reference set. In the case of HDE 245059, Padgett (1996) obtained the photospheric iron abundance \([\text{Fe}/\text{H}]\) = \(-0.07 \pm 0.13\) using as reference set the solar photospheric abundances from Grevesse (1984). Using the revised reference set of Grevesse & Sauval (1998), the stellar photospheric abundance is \([\text{Fe}/\text{H}]\) = +0.10. Our coronal abundances have been obtained from the best fit to the zeroth-order, MEG\(\pm 1\), and HEG\(\pm 1\) using as reference set the solar photospheric values from Grevesse & Sauval (1998). We have obtained an iron abundance of \([\text{Fe}/\text{H}]\) = \(-0.64\). Thus, the difference between the photospheric and coronal values is \([\text{Fe}/\text{H}]_{\text{photospheric}} - [\text{Fe}/\text{H}]_{\text{coronal}}\) = +0.74; i.e., the coronal iron abundance is 5.5 lower than the photospheric one. This result is consistent with the inverse FIP effect expected in young magnetically active stars.

6. SUMMARY AND CONCLUSIONS

We have obtained the Chandra high-resolution spectrum for HDE 245059. Thanks to our X-ray and near-infrared data we have resolved this X-ray luminous WTTS to be a binary. We have attempted to get an estimate of the properties of the single components of the HDE 245059 binary based in the combination of the infrared magnitude differences, evolutionary models and SED determination. Our analysis gave a system of \( \approx 2 - 3 \) Myr with masses \( M_N \approx 3 \ M_\odot \) and \( M_S \approx 2.5 \ M_\odot \), rather high values for low-mass PMS stars. This is the first attempt to constrain the binary component masses, further studies are needed to obtain more accurate estimates.

In the X-rays we were able to resolve both binary components in the zeroth-order image and in the grating spectra. We have analyzed the zeroth-order spectrum for each component of the binary using a multi-T plasma model. For the northern star we have found a temperature between \(-6 \text{ to } -40 \) MK, the
dominating component being a plasma between ~6 and ~13 MK. For the southern star, we have found temperatures between ~8 and ~34 MK.

During our observations, split in three runs, we have detected a flare from the southern star, the fainter of the system in average. An analysis of the zeroth-order spectrum of this star during the flare has gave a plasma with a temperature of ~30 MK, consistent with the high temperature component obtained for the quiescent state, and a luminosity higher by a factor of ~5 when compared with the quiescent state.

We have derived the properties of the plasma from the combined zeroth-order, MEG±1, and HEG±1 data for the binary during the quiescent state. We have analyzed the spectrum using three methods: a continuous emission measure distribution from Chebyshev polynomials, a continuous emission measure distribution approximated by two power laws, and the classical from Chebyshev polynomials, a continuous emission measure distribution approximated by two power laws, and the classical.

An analysis of the zeroth-order spectrum of this star during the quiescent state. We have analyzed the spectrum us-

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