Astron. Astrophys. 347, 178–184 (1999)

ASTRONOMY
AND
ASTROPHYSICS

TT Arietis: the low state revisited*

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Received 26 February 1999 / Accepted 29 April 1999

Abstract. We present optical and ultraviolet spectroscopy of TT Ari obtained during the 1982−85 low state. In November/December 1983, accretion had almost completely ceased, unveiling both the white dwarf and the secondary star. The IUE spectrum obtained during that occasion contains absorption lines of Lyα, Si IV, C IV, and He II. We derive a photospheric temperature of $T_{\rm wd} = 39\,000$ K and find the abundances of Carbon and Helium to be 0.5 and 2.0 times solar, respectively. An upper limit of $v \sin i \lesssim 750\,{\rm km\,s^{-1}}$ is derived from the metal line profiles. Comparison with the IUE spectrum taken one year earlier during the low state shows no evidence for cooling of the white dwarf over a time span of one year. The optical spectrum displays Balmer absorption lines from the white dwarf, overlayed with narrow emission lines, as well as the TiO absorption bands of the secondary star, for which we derive a spectral type M3.5±0.5. A distance of $d = 335 \pm 50$ pc is derived from both, the white dwarf and the secondary star. The data indicate that the low-state accretion disc in TT Ari was optically thin at least for $r \lesssim 12 R_{\rm wd}$.

Key words: accretion, accretion disks – stars: binaries: close – stars: individual: TT Ari – stars: novae, cataclysmic variables – ultraviolet: stars

1. Introduction

Novalike variables are cataclysmic variables (CVs) in which a nonmagnetic white dwarf accretes matter from a late-type secondary star through an accretion disc at a relatively high mass-transfer rate ($\dot{M} \approx 10^{-9}\,M_\odot\,{\rm yr}^{-1}$). The high mass-transfer rate in novalike variables keeps their accretion discs permanently in a hot state. Therefore, in contrast to their low-mass-transfer relatives, the dwarf novae, novalike variables do not show disc outbursts. Thus, among CVs, the accretion discs in novalike variables are probably closest to a "steady state", and represent favourable test-cases for accretion disc theory. Nevertheless, this advantage has an important drawback: in contrast to dwarf novae, where basic properties of the accreting white dwarf (and sometimes of the donor star) can be determined from observations during quiescence, the bright accretion disc in novalike variables totally outshines the two stellar components, and relatively little is known about their properties. Alas, a full confrontation of accretion disc theory with observations requires the knowledge of e.g. the white dwarf temperature, rotational velocity and mass, as these properties have fundamental influence on the structure of the disc-star interface, the boundary layer, and of the disc itself. A solution to this dilemma is offered by the VY Scl stars, a subgroup of novalike variables in which the brightness drops by several magnitudes at random occasions, due to a decrease in the mass-transfer rate. During these occasions, the two stellar components may be directly viewed.

TT Ari, one of the brightest CVs in the sky, is a VY Scl star: classified as a novalike variable (Cowley et al. 1975), it dipped in 1980 shortly from the usual brightness $V \approx 10.5$ to $V \approx 14$ (Krautter et al. 1981). In March 1982, the system plunged into a deep low state, $V \approx 16$, where it remained until March 1985. Optical and UV spectroscopy obtained in late 1982 revealed the white dwarf photospheric emission and lead to an estimate of $50\,000\,{\rm K} \lesssim T_{\rm wd} \lesssim 80\,000\,{\rm K}$ (Shafter et al. 1985, hereafter S85). However, no spectroscopic signature of the secondary star was detected.

In this paper, we report optical and UV spectroscopy obtained in late 1983 during an occasion when accretion had (almost) completely ceased and the system reached the lowest level of activity recorded so far. From these data, we put tighter constraints on the white dwarf temperature, estimate the chemical abundances in its photosphere, derive an upper limit on its rotational velocity, infer the distance of TT Ari, and discuss the structure of the accretion disc during the low state.

2. Observations

2.1. UV spectroscopy

TT Ari was observed twice with IUE during the 1982–85 low state (Table 1). During both occasions, a pair of SWP and LWP/R spectra were obtained in the low-resolution mode (FWHM ≈ 6 Å) through the large aperture. The 1982 spectra were previously discussed by S85, the 1983 spectra were taken by one of us (J.K.). All spectra were retrieved from the IUE

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* Based on observations made with the International Ultraviolet Explorer, retrieved from the IUE FA and on observations at the European Southern Observatory La Silla (Chile) with the 1.5-m

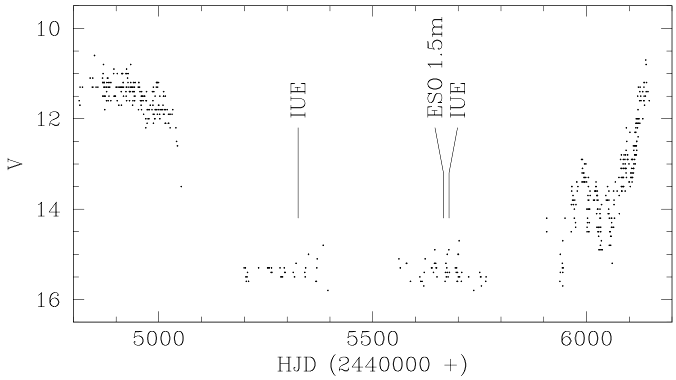

Fig. 1. Optical long term light curve of TT Ari from AAVSO data, kindly provided by J. Mattei (1998). The times of IUE and optical spectroscopy are indicated.

Table 1. Log of the IUE observations of TT Ari obtained during the 1982–85 low state. Listed are the IUE image number, the observation date, and the exposure time

Image No.	Exposure start	Exp. time [sec]
LWR14868L	Dec 22 1982	8880
SWP21742L	Dec 22 1982	14400
LWP02383L	Dec 10 1983	9720
SWP21742L	Dec 10 1983	14400

Table 2. Emission-line measurements of TT Ari in the low state. N27 and N29 denominate the values measured from the spectra obtained on 1983, November 27 and 29, respectively.

Line	λ [Å]	FWHM [Å]		Flux[2)]		E.W. [Å]	
		N27	N29	N27	N29	N27	N29
He I	7065	–	12	–	39	–	7
He I	6678	–	12	–	47	–	7
Hα	6562	14	16	326	680	65	91
He I	5876	8	16	23	130	4	17
He I,Fe II	5016,18	–	14	–	39	–	4
He I,Fe II	4922,24	–	15	–	45	–	4
Hβ	4861	11	15	141	502	17	42
He I	4471	–	11	–	55	–	4
Hγ	4340	10	16	65	410	5	26
Hδ	4102	–	16	–	328	–	16
Hϵ,Ca II H	3970	–	13	–	224	–	9

[2)] in $10^{-16}\,\mathrm{erg\,cm^{-2}s^{-1}}$

Final Archive. Both SWP spectra have almost identical continuum slopes and fluxes (Fig 2). However, while the 1982 spectrum contains C IV λ 1549, Si IV $\lambda\lambda$ 1393, 1403 and He II λ 1640 in emission, our spectrum contains all these lines in absorption. The LWP/R spectra are also very similar in continuum slope and flux. Both spectra contain Mg II λ 2880 emission, which is, however, weaker in the 1983 data than in the 1982 data.

The weakness/absence of emission lines indicates that accretion had ceased almost totally during our December 1983 observations.

2.2. Optical spectroscopy

Optical low-resolution (FWHM≈9 Å) spectroscopy of TT Ari was obtained on 1983 November 27 and 29 with the 1.5 m telescope of the European Southern Observatory at La Silla using the Image Dissector Scanner. During both nights, twelve spectra were obtained with typical exposure times of ≈ 6 min. As the individual spectra are of poor signal-to-noise ratio and cover only part of the binary orbit, we decided to use only the average spectra of each night (Fig. 3). During the night of Nov. 27, TT Ari was faint with very weak Balmer lines and almost no emission of He I. The magnitude computed from the average spectrum was $V \approx 16.8$, similar to the low-state spectrum reported by S85 (their Fig. 8), from which we measure $V \approx 16.7$. Also the weak, rather narrow absorption lines of Hβ and Hγ are similar to the spectrum of S85. While S85 could not confidently claim the detection of any spectral features from the secondary star, the contribution of the late-type star clearly dominates the red end of our spectrum.

On Nov. 29, TT Ari was somewhat brighter, $V \approx 16.5$, with relatively strong Balmer emission and noticeable emission of He I, comparable to the line emission in the low state spectrum of S85. No emission from He II is observed. Line measurements are summarized in Table 2. We do not detect Fe II λ 5169, hence, He I $\lambda\lambda$ 4922,5016 are probably fairly uncontaminated by emission of Fe .

3. Analysis and results

3.1. The white dwarf

We use the SWP spectrum obtained in December 1983 to determine the effective temperature and the chemical surface abundances of the white dwarf. A previous estimate of the white dwarf temperature was published by S85. They derived a lower limit of $T_{\rm wd} \geq 50\,000$ K by comparing optical low-state spectroscopy of TT Ari obtained in December 1982 with observations of the hot white dwarf G191-B2B. S85 also noted absorption of He II λ 4686 in their spectra and ascribed it to photospheric absorption by freshly accreted material; from the relative weakness of these lines, they derived an upper limit of $T_{\rm wd} \leq 80\,000$ K. Considering that the SWP spectrum obtained in December 1983 shows no emission lines, it appears likely that accretion had switched off totally during the observations, and that the white dwarf entirely dominates the UV. Hence, the observed metal absorption lines are probably of photospheric origin.

We fitted the December 1983 IUE spectrum in two steps, using model spectra computed with the codes TLUSTY and SYNSPEC (Hubeny 1988, Hubeny & Lanz 1995): (a) in a first step, we determined the white dwarf temperature from a grid of model spectra calculated for solar abundances and $\log g = 8$, yielding the best fit for $T_{\rm wd} = 39\,000$ K. (b) Fixing the temperature to 39 000 K, we changed the abundances in order to match the observed absorption lines of Si IV $\lambda\lambda$ 1393,1403, C IV λ 1550 and He II λ 1640. The fit implies solar abundances, except for Helium (2 times solar) and Carbon (0.5 times solar) and Iron

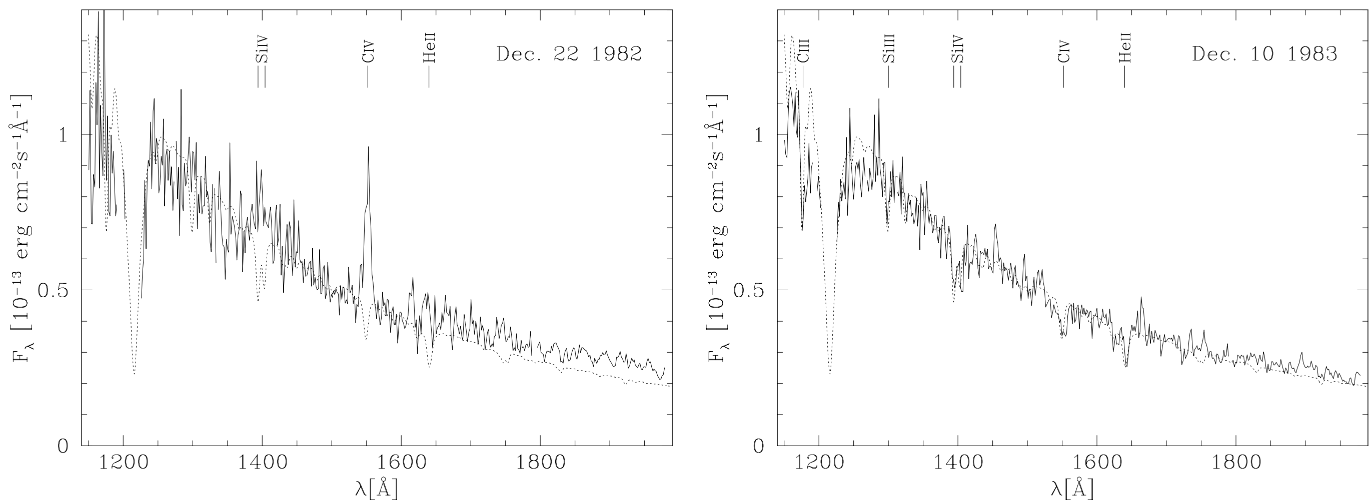

Fig. 2. IUE SWP spectra of TT Ari obtained during the 1982–85 low state. The spectrum shown in the *left panel* has been previously discussed by S85. Plotted as dashed line in *both panels* is the best-fit white dwarf model derived from the December 1983 observations. The geocoronal emission lines have been omitted.

(0.01 times solar). The errors in abundances are rather large, probably of order ± 1, but the relative deviations from element to element are almost certainly real. The best fit achieved using a single temperature exceeds the observed flux somewhat in the 1250–1300 Å range (Fig. 2, right panel). We show the same best-fit model along with December 1982 data in the left panel of Fig. 2. Even though we did not formally fit the 1982 IUE spectrum, it is apparent that the temperature of the white dwarf did not vary significantly between the two observations separated by one year. The white dwarf model derived from the 1983 SWP continuum and Lyα width is in very good agreement also with the optical spectrum obtained on 1983, Nov. 27 (Fig. 4). The S/N of our optical spectra is too low to detect any absorption from He I,II. The formal error in the temperature derived from the fit is ± 2000 K. However, from the present data, it is not possible to independently derive the surface gravity, and, hence the mass of the white dwarf in TT Ari. Allowing for $\log g = 9$ (7) yields temperatures higher (lower) by 3000–5000 K.

We have also attempted a determination of the rotational velocity of the white dwarf from the narrow absorption lines of Si IV, C IV and He II. Due to the rather limited spectral resolution of IUE, only an upper limit of $v \sin i = 750\,\mathrm{km\,s^{-1}}$ can be derived. However, this low velocity clearly excludes the possibility that the metal lines originate in the inner accretion disc.

3.2. The secondary star and the distance of TT Ari

The clear detection of TiO absorption bands from the secondary star allows to derive its spectral type. We have fitted the optical spectrum obtained on 1983, Nov. 27 with a composite model consisting of a white dwarf model spectrum, an observed M-dwarf spectrum selected from a sequence of observed standard stars, and Gaussian emission lines of Hα, Hβ and Hγ. The temperature of the white dwarf model was fixed to 39 000 K, as derived from the 1983 IUE data. We left the scaling factor of the white dwarf model free to account for a possible mismatch in the overall flux calibration between the optical data and the IUE spectrum. However, the best fit reproduces the SWP IUE flux level within less than 5%. The best fit is achieved selecting the M-dwarf Gl 273 as template for the secondary star, scaled to $V = 19.07 \pm 0.1$ (Fig. 4). The spectral type of Gl 273 is M3.5 (Kirkpatrick et al. 1994), we estimate the uncertainty in the spectral class of the secondary star in TT Ari to be ± 0.5. At $P_{\rm orb} = 3.3$ h, the secondary star in TT Ari appears to be close to the main sequence (see also Beuermann et al. 1998).

The distance to TT Ari was previously rather uncertain, with estimates ranging from 100 pc (Jameson et al. 1982) to 400 pc (S85). We use here the new distance determination method presented by Beuermann & Weichold (1998), which is based on the surface brightness of the flux difference due to the $\lambda\lambda$ 7500/7165 Å TiO band, i.e.

$$\frac{f_{\rm TiO}}{F_{\rm TiO}} = \frac{{R_{\rm sec}}^2}{d^2}, \qquad (1)$$

where $f_{\rm TiO}$ and $F_{\rm TiO}$ are the observed flux difference of the $\lambda\lambda$ 7500/7165 Å TiO band and the corresponding surface brightness on the stellar surface, respectively, and $R_{\rm sec}$ is the radius of the secondary star. From the best fit (Fig. 4), we measure $f_{\rm TiO} = (2.2 \pm 0.2) \times 10^{-16}\,\mathrm{erg\,cm^{-2}s^{-1}\mathring{A}^{-1}}$. With $\mathrm{Sp} = 3.5 \pm 0.5$ we obtain $F_{\rm TiO} = (3.5 \pm 0.4) \times 10^5\,\mathrm{erg\,cm^{-2}s^{-1}\mathring{A}^{-1}}$ from Beuermann & Weichold (1998). As the secondary star is close to the main sequence, its radius can rather safely be derived from Roche geometry and ZAMS stars (Patterson 1984; Beuermann & Weichhold 1998; Baraffe et al. 1998), $R_{\rm sec} = (2.6 \pm 0.18) \times 10^{10}$ cm, with the error due to the uncertainty in the ZAMS relation. The resulting distance is $d = 335 \pm 50$ pc.

An independent check on this distance estimate can be derived from the white dwarf model fitted to the December 1983 SWP spectrum, using the flux scaling factor

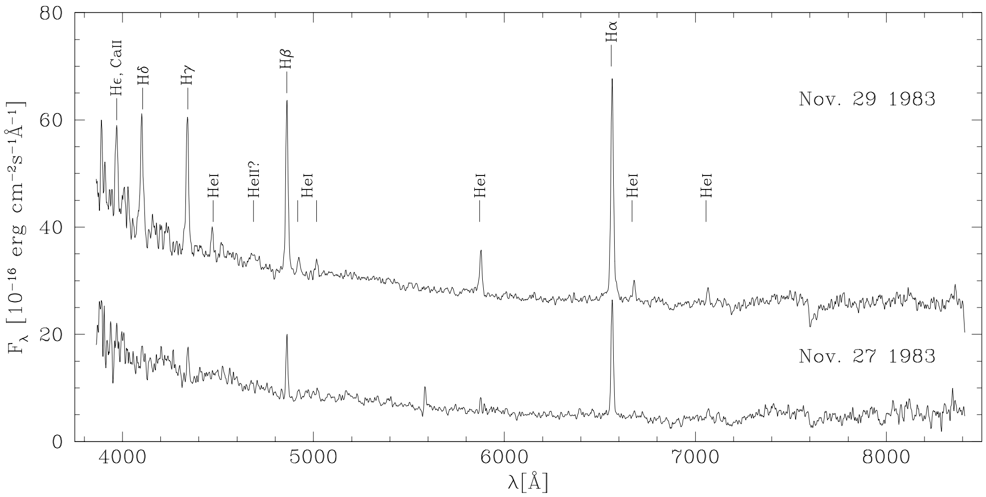

Fig. 3. Optical spectra of TT Ari obtained on 1983 Nov. 27 and 29, major emission lines are indicated. The Nov. 29 spectrum is shifted upwards by 20 units.

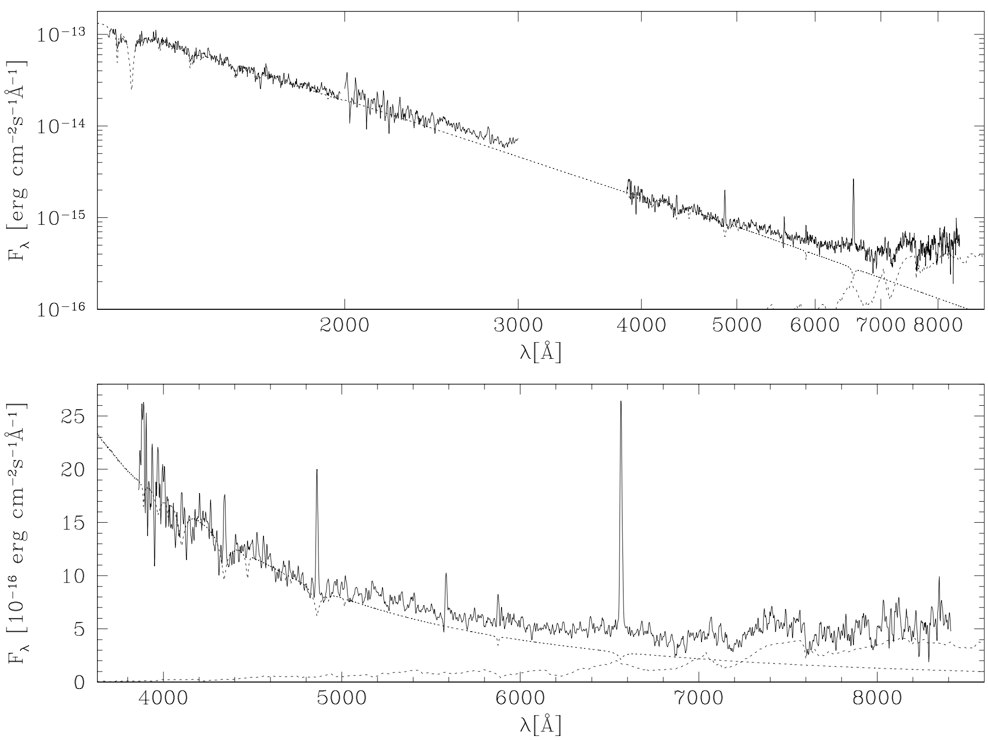

Fig. 4. Composite fit to the low state spectrum of TT Ari. *Top:* the IUE spectra from 1983, December 22 and the optical spectrum from 1983, Nov. 27. *Bottom:* blow-up of the optical spectrum. Shown as dotted lines are the best-fit white dwarf ($T_{\rm wd}$=39 000 K, $\log g = 8$) and the best fit secondary star (Gl273).

$$\frac{f}{H} = 4\pi \frac{{R_{\rm wd}}^2}{d^2}, \qquad (2)$$

where f and H are the observed flux and the Eddington flux of the model, respectively. Assuming $\log g = 8$ implies $M_{\rm wd} \approx 0.6\,M_\odot$ and $R_{\rm wd} \approx 8.4 \times 10^8$ cm. The distance computed from the best fit to the SWP spectrum is $d = 280$ pc. Assuming an extremely low ($M_{\rm wd} = 0.35 M_\odot \Leftrightarrow R_{\rm wd} = 1.1\times10^9$ cm) or an extremely high ($M_{\rm wd} = 1.2 M_\odot \Leftrightarrow R_{\rm wd} = 3.9\times10^8$ cm) white dwarf mass results in $d = 385$ pc and $d = 125$ pc, respectively. This agrees, whithin the errors, with the value derived above.

3.3. The origin of the optical emission line spectrum

TT Ari showed a considerable change in activity within the two nights of our observations. On Nov. 27, the line emission is very weak, and the overall UV-optical spectrum can be very well fitted with a white dwarf/M dwarf composite model (Fig. 4). Apart from Hα the emission lines are probably not resolved. The spectrum taken on Nov. 29 closely resembles that presented by S85, with an additional continuum component as well as strong Balmer and He I emission. The higher spectral resolution of their data allowed S85 to discern two components of the Hα emission line, a stronger "peak" and a weaker "base". Radial velocity measurements showed that both components vary in phase, with the "peak" component having a relatively low semiamplitude. The phase of the radial velocity curve in the low state is offset by 180° with respect to the high state, where the emission lines are thought to originate in the disc. S85 interpreted the "base" to originate from the chromosphere of the secondary star and the "peak" component from material almost in rest in the binary

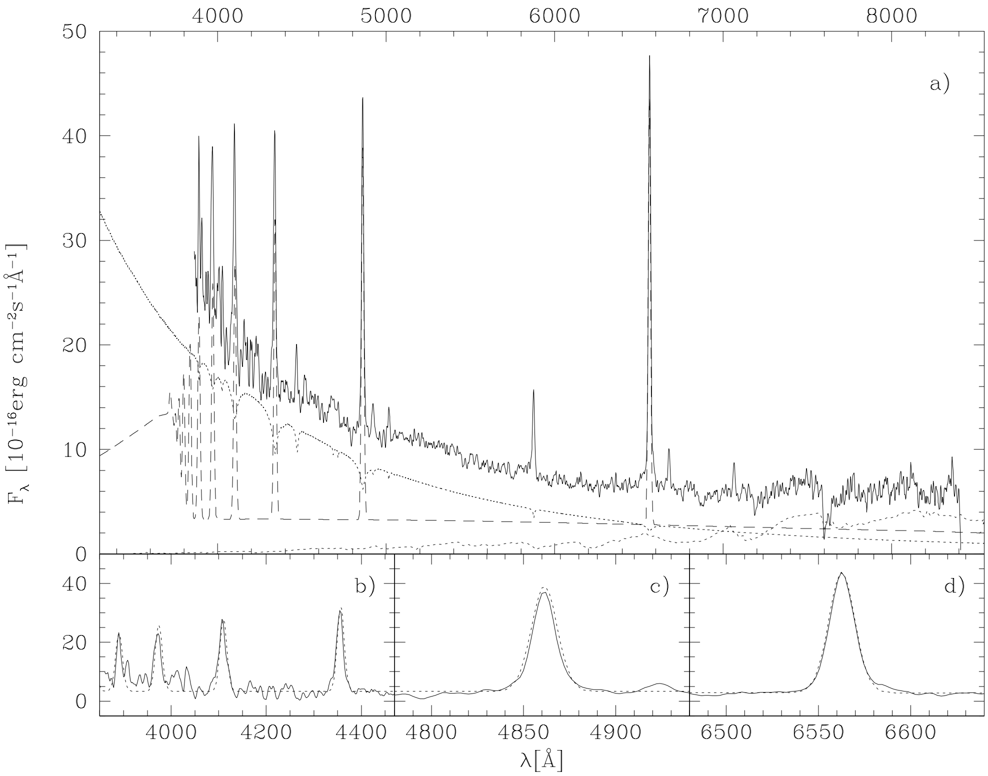

Fig. 5a–d. Three-component fit to the Nov. 29 spectrum. The spectra of the white dwarf and the secondary star (dotted) are taken from Fig. 4. The additional continuum and the Balmer lines are fitted by the emission of an isothermal, isobaric slab of $T = 6500\,\mathrm{K}$, $\Sigma = 0.043\mathrm{g\ cm}^{-2}$, and a radius of 6.5×10^{10} cm (dashed line). The *bottom panels* show the sum of the three components along with the observed Balmer lines.

frame, e.g. located close to centre of mass or in a circumbinary shell/ring.

Here, we hypothesize that the weak emission lines on Nov. 27 may, indeed, originate on the secondary star, as it was also proposed by Robinson et al. (1981) for the faintest state of MV Lyr. The additional emission observed on Nov. 29 is then most likely due to slightly enhanced mass transfer and thus comes from the disc.

Considering that the Nov. 29 spectrum resembles that of a quiescent dwarf nova, we fitted it with the two stellar components derived above plus the model spectrum of an isothermal, isobaric pure-hydrogen slab representing the disc. The flux is computed from $B_\lambda(T)(1-\exp(-\tau_\lambda))\,\Omega$, where $B_\lambda(T)$ is the Planck function, τ_λ is the wavelength-dependent optical depth, and Ω is the solid angle subtended by the slab. The optical depth is $\tau_\lambda = h\rho\kappa_\lambda/\cos i$, h is the height of the slab, ρ the density, κ_λ the mass absorption coefficient (including free-free, bound-free and bound-bound absorption of H I as well as H^- absorption), and i the binary inclination. The opening angle is given by $\Omega = \pi R_\mathrm{d}^2/(d^2\cos i)$, with R_d the slab radius and d the distance. We chose $d = 335\,\mathrm{pc}$ as derived above and $i = 30°$ (S85). Free fit parameters are the temperature T, the density ρ and the slab height h. However, the effects of ρ and h on the emitted spectrum are anticorrelated, with almost identical spectra for $\Sigma = \rho h = \mathrm{const}$. Stark broadening is included in the computation of the bound-bound absorption coefficient, but does not significantly contribute to the line width at the densities considered below. As we only need to fit the line and continuum fluxes, we convolve the spectrum with a 7 Å FWHM Gaussian to match the observed line profiles.

The Nov. 29 spectrum can be well fitted with $T = 6500\,\mathrm{K}$, $\Sigma = 0.043\,\mathrm{g\,cm}^{-2}$, and $R_\mathrm{d} = 6.5 \times 10^{10}$ cm. The spectrum of the isothermal slab is optically thick in Hα–Hϵ and optically thin in the continuum. The temperature and density are the same as derived from a spectrum of the dwarf nova EK TrA in quiescence (Gänsicke et al. 1997), underlining the similarity between TT Ari in the low state and a quiescent dwarf nova. The assumed value of $h = 1.15 \times 10^8$ cm can be increased by a factor 100 (with a corresponding decrease in ρ) without significant changing in T or R_d. Disc heights much larger than 10^9 cm are probably unreasonable. A temperature of $6000-7000$ K is theoretically expected for a low mass-transfer accretion disc, with the emitted spectrum being, as observed, optically thin in the continuum and optically thick in the Balmer lines (Williams 1980). Low disc temperatures and optically thin emission were verified in several quiescent dwarf novae, e.g. OY Car, Z Cha (Wood 1990) and HT Cas (Wood et al. 1992). However, a number of problems exist in modelling the quiescent emission from dwarf novae with simple LTE disc models; see the papers by Wood et al. (1992) and Marsh (1987) for a thorough discussion. Taking $M_\mathrm{wd} = 0.6\,M_\odot$, $M_\mathrm{sec} = 0.25\,M_\odot$, and $P_\mathrm{orb} = 3.30\,\mathrm{h}$, the Roche-lobe of the white dwarf is $R_L = 4.4 \times 10^{10}$ cm, which 30% smaller than R_d. Though increasing M_wd and i or decreasing d reduces this discrepancy, our value of R_d cm should be regarded as a very crude estimate, as our "disc model" does not include any temperature variation accross the disc.

The luminosity of the isothermal slab is $L_\mathrm{d} = 4.9 \times 10^{31}\,\mathrm{erg\ s}^{-1}$, which corresponds to an accretion rate of $\dot{M} \approx 4.0 \times 10^{-12}\,M_\odot\,\mathrm{yr}^{-1}$, assuming $M_\mathrm{wd} = 0.6\,M_\odot$ and that half of the gravitational energy is released in the disc. This luminosity is an order of magnitude below that expected for gravitational braking, indicating that the mass transfer through the disc is extremely reduced during the low state. It is interesting to note that $L_{\rm d}$ is also an order of magnitude below the fraction of the white dwarf luminosity intercepted by the disc. The effect of irradiation by the primary will be further discussed below.

4. Discussion

4.1. The white dwarf

The apparent absence of a measurable change in $T_{\rm wd}$ of the white dwarf from fitting the two IUE spectra taken a year apart suggests two possible interpretations; (1) either the white dwarf cooled substantially during the 280 day interval between the start of the low state and the time of the first IUE spectrum, or (2) the white dwarf is in fact heated to a much greater depth then either WZ Sge or AL Com and hence cooling proceeds much more slowly and was not measurable during the 1 year interval between the two IUE spectra. If we take the 280 d interval as the upper limit to the thermal e-folding time, then the implied amount of envelope heating places TT Ari within the range of e-folding times measured for several white dwarfs in dwarf novae. If for example $\tau = 280\,{\rm d}$, then only WZ Sge and AL Com cool more slowly, suggesting that their high amplitude outbursts produced heating to a greater depth than that which occurs during extended quasi-steady accretion in TT Ari in its high state. On the other hand, during the long term high state accretion, the accretional heating of the white dwarf may have reached an equilibrium with cooling by radiation at the observed $T_{\rm wd}$ of 39,000 K, in which case a much longer low state interval is required to measure the cooling of the white dwarf.

The IUE/SWP spectrum of TT Ari allowed a significant detection of heavy elements in the photosphere of the white dwarf. For $T_{\rm wd} = 39\,000\,{\rm K}$, radiative levitation cannot be ruled out completely but is unlikely to be responsible for the observed heavy elements (for a recent discussion on radiative levitation in single (hot) white dwarfs, see Wolff et al. 1998). Gravitational diffusion in an H-rich white dwarf at $T_{\rm wd} = 39\,000\,{\rm K}$ occurs on time scales of a few days, much shorter than one year (the time passed between the end of the high state and our IUE observation). Thus, for an accretion time scale longer than the diffusion time scale, the chemical abundance of accreted species provides information on the accretion rate. Ongoing accretion at a low level can replenish the photosphere with heavy elements. We estimate the equilibrium accretion rate (assuming accretion-diffusion equilibrium) needed to account for the observed abundances, using the methods described by Sion et al. (1998b). The rate we estimate is $\sim 10^{-16} - 10^{-15}\,M_{\odot}\,{\rm yr}^{-1}$. This rate is essentially the Bondi-Hoyle fluid rate that an isolated white dwarf would experience as it traverses a dense molecular cloud. It appears entirely plausible that matter is accreted by the white dwarf in TT Ari at such a minute rate during a low state when the disk seems to be largely absent.

Even though the quality of the IUE spectra does not allow a detailed analysis of the white dwarf chemical composition, the pattern we found, within the uncertainties, is similar to that in the two dwarf novae VW Hyi (Sion et al. 1997) and U Gem (Sion et al. 1998a): a depletion of C with respect to N by a factor of 8–10. In the case of the two dwarf novae, Sion et al. (1997, 1998a) argued convincingly that the observed abundance patterns are consistent with thermonuclear processing during a past nova event on the white dwarf surface and contamination of the secondary during the post-nova common envelope phase. Whether such a model also applies to TT Ari can only be tested definitively by a dedicated HST observation of the system during a future low state.

Hollander & van Paradijs (1992) propose that the $\sim 20\,{\rm min}$ quasi-periodic oszillations (QPOs) observed in the optical as well as at X-ray wavelengths (e.g. Baykal et al. 1995; Semeniuk et al. 1987) are due to the beat between the white dwarf spin period and the period at the inner edge of the (truncated) disc, which will be bona-fide rotating at Keplerian velocity. From the observations, Hollander & van Paradijs estimate $P_{\rm spin} \sim 200$–$300\,{\rm s}$. The implied rotational velocity, $v\sin i \approx 130\,{\rm km\,s^{-1}}$for $R_{\rm wd} = 8.4\times10^8$ cm and $i = 30°$, is far below our upper limit $v\sin i \lesssim 750\,{\rm km\,s^{-1}}$derived from the doppler-broadening of the Si IV, C IV and He II lines. However, our IUE spectroscopy shows that high-resolution UV spectroscopy obtained during a future low state of TT Ari will allow a direct measurement of the white dwarf spin.

4.2. How much of an accretion disc is there during the low state?

King (1997) showed that irradiation from a hot white dwarf may strongly affect the structure of a low mass-transfer accretion disc: the inner region of the disc will be heated sufficiently to be permanently in a hot, ionized state, enforcing a high mass-transfer rate in this region. This results in the disc being drained up to a truncation radius, $R_{\rm tr}(T_{\rm wd})$, which is a function of the white dwarf temperature. This truncation may cause the UV delay observed in dwarf novae (King 1997) and could lead to complete depletion of the disc in VY Scl stars during their low states (King & Cannizzo 1998; Leach et al. 1999).

Our low-state observations allow us to tackle the question "how much of the disc may be optically thick?" If the whole accretion disc were optically thick, its radial temperature distribution would be given approximately by

$$T_{\rm d}^4(r) = T_{\dot M}^4(r) + T_{\rm irr}^4(r). \qquad (3)$$

where

$$T_{\dot M}(r) = \left(\frac{3GM\dot M}{8\pi r^3\sigma}[1-\sqrt{\tilde r}]\right)^{1/4} \qquad \text{with } \tilde r = R_{\rm wd}/r \qquad (4)$$

represents the flux due to viscous dissipation (e.g. Pringle 1981), and

$$T_{\rm irr}(r) = T_{\rm wd}\left(\frac{1}{\pi}(1-\beta)\arcsin\tilde r - \tilde r\sqrt{1-\tilde r^2}\right)^{1/4}, \qquad (5)$$

accounts for the irradiation by the white dwarf (e.g. Adams et al. 1988), with β the albedo of the disc. We compute the disc by integrating blackbody spectra over 50 rings spaced logarithmically in r. In the following, we chose $M_{\rm wd} = 0.6\,M_\odot$, $d = 335$ pc, $i = 30°$, and the outer disc radius $R_{\rm out} = 3 \times 10^{10}\,{\rm cm} \approx 35 R_{\rm wd}$.

We take the luminosity of the optically thin component (Sect 3.3) as a measure for the accretion rate, $\dot{M} = 3 \times 10^{-12}\,M_\odot\,{\rm yr}^{-1}$, and assume $\beta = 0.5$. For such a low $\dot{M}$, irradiation totally dominates the temperature in the disc, keeping the inner $\sim 6\,R_{\rm wd}$ hotter than 6500 K, i.e. in the ionized, high mass-transfer state. Composite model spectra for TT Ari are obtained by summing the fluxes of the white dwarf and the M dwarf (as dertermined in Sect 3.1, 3.2), and the blackbody disc spectrum.

In the extremest case, the optically thick disc extends down to the white dwarf, $R_{\rm in} = R_{\rm wd}$, which results in the flux of the composite model exceeding the observed flux by more than a factor two in the UV range and the Nov. 27 optical flux by more than a factor of three. If, as suggested by King (1997), the disc is truncated for $r < R_{\rm tr} = 6 R_{\rm wd}$, its contribution to the UV is negligible. However, at optical wavelengths, the disc emission is comparable to that of the secondary star, and the composite model exceeds the Nov. 27 observations by a factor ≈ 2. In order for the composite model to be consistent with the Nov. 27 optical spectrum, the disc has to be truncated at $r \sim 12 R_{\rm wd}$. The presence of an optically thick cold ($T \leq 3000$ K) disk at radii $r \gtrsim 12 R_{\rm wd}$ can not be excluded. Using the isothermal slab model discussed in Sect 3.3, we estimate that the column density in the inner disc ($r \lesssim 15 R_{\rm wd}$) must be $\Sigma < 0.3\,{\rm g\,cm^{-2}}$ in the regions with $T(r) \gtrsim 10\,000$ K and $\Sigma < 5\,{\rm g\,cm^{-2}}$ where $T(r) \lesssim 10\,000$ K.

Hameury et al. (1998) argue that irradiation by the hot white dwarf will decrease the surface density in the inner region of the disc, but *not* to the point that it becomes optically thin. The authors point out that the albedo of the disc may be higher, and that irradiation from the hot white dwarf may result in a hot corona instead of a deep heating of the disc. However, the optically thin component discussed in Sect. 3.3 is not very hot and its luminosity corresponds to only ~ 10 % of the white dwarf flux irradiating the disc, so that does not seem likely that it could shield underlying optically thick material from irradiation by the white dwarf.

An additional clue that the observed optically thin emission does not originate in the inner disc comes from the relatively narrow emission lines (Table 2). Assuming $M_{\rm wd} = 0.6\,M_\odot$, $i = 30°$, and Keplerian orbits, these lines can not arise from regions with $r \lesssim 9\,R_{\rm wd}$. We conclude that in the low state, the inner accretion disc in TT Ari is drained to a large extent.

5. Conclusion

We have analysed optical and IUE spectroscopy of TT Ari obtained in November/December 1983 during the long 1982–85 low state. We find that the white dwarf has an effective temperature of 39 000 K, much lower than the previous estimate, and that there is no evidence that it cooled throughout the low state. The IUE spectrum provides an upper limit on the white dwarf rotation of $v \sin i \lesssim 750\,{\rm km\,s^{-1}}$. The distance of TT Ari is estimated to be $d \approx 335 \pm 50$ pc, derived from the brightness of the secondary star detected in the optical spectrum. The combined UV/optical spectrum indicates that a rather large part of the inner accretion disc is drained, consistent with models for irradiated discs.

Acknowledgements. We thank F.V. Hessman, J. Kube, and the referee C. la Dous for critical comments on an earlier draft of this paper. In this research we have used data from the AAVSO International Database operated at AAVSO Headquarters. These observations are provided to the AAVSO by variable star observers worldwide. This work was supported in part by the BMBF/DLR under project number 50 OR 9210 1.

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