Evidence for high accretion-rates in Weak-Line T Tauri stars?

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ABSTRACT
We have discovered T Tauri stars which show startling spectral variability between observations separated by 20 years. In spectra published by Bouvier & Appenzeller (1992) these objects showed very weak H\textalpha emission, broad CaII absorption and so called “composite spectra”, where the spectral type inferred from the blue region is earlier than that inferred from the red. We present here new spectroscopy which shows that all four stars now exhibit strong H\textalpha emission, narrow CaII emission and a spectral type which is consistent at all wavelengths.

We propose a scheme to understand these changes whereby the composite spectra of these stars can be explained by a period of active accretion onto the central, young star. In this scheme the composite spectrum consists of a contribution from the stellar photosphere and a contribution from a hot, optically thick, accretion component. The optically thick nature of the accretion flow explains the weakness of the H\textalpha emission during this phase. Within this scheme, the change to a single spectral type at all wavelengths and emergence of strong H\textalpha emission are consistent with the accretion columns becoming optically thin, as the accretion rate drops. There is a strong analogy here with the dwarf novae class of interacting binaries, which show similar behaviour during the decline from outbursts of high mass-transfer rate.

The most important consequence of this interpretation is that these objects bring into question the association of Weak-Line T Tauri stars (WTTs) with non-accreting or discless objects. In light of this result we consider the justification for this paradigm.

Key words: accretion, accretion disks, stars:pre-main-sequence, instabilities, stars:dwarf novae, planetary systems: protoplanetary discs

1 INTRODUCTION

T Tauri stars are divided into classical T Tauri stars (CTTs) and weak T Tauri stars (WTTs) largely on the basis of their H\textalpha emission. The cutoff is usually taken at 10\AA, with values above this representing a CTTs (Appenzeller & Mundt 1989). It has long been argued that the difference between CTTs and WTTs is that the former have discs, and the latter do not. Indeed, there is some support for this paradigm, with H\alpha equivalent width correlating with other disc indicators, such as B-V excess, or infrared colour excess (Herbig 1998; Cabrit et al. 1990). However, many problems exist with such a scheme. The cutoff of 10\AA is somewhat arbitrary, and is less sensitive at earlier spectral types (Martín 1997). Also, recent studies have discovered WTTs which show infrared excesses indicative of circumstellar discs (Gregorio-Hetem & Hetem 2002). Here we present evidence that at least some WTTs not only possess accretion disks, but are accreting from them at a rate which is comparable to the most rapidly accreting CTTs.

An optical spectroscopic and photometric survey of a set of 47 stars associated with Einstein X-ray sources in the \( \rho \) Ophiuchus cloud (Bouvier & Appenzeller 1992, hereafter BA92), identified 30 pre-main sequence stars. Four of these stars (ROXs 21, ROXs 47a, ROXs 2 and ROXs 3) were identified as exhibiting “composite” spectra - the spectral type inferred from a blue spectral region near H\beta was systematically earlier than that inferred from a red spectral region surrounding the TiO band between 7050 and 7200\AA. The
spectral types inferred for these stars are listed in Table 1. We note here that the composite spectrum effect was reliably detected in the case of ROXs 21, 47a and 3. The detection of the effect in ROXs 2 was less secure; although the blue spectral type of K3 was reliable, the lower resolution spectrum of this object rendered the red spectral type of M0 uncertain. Our spectrum published here confirms the red spectral type of BA92, and hence we consider this star as a bona-fide composite spectrum object. BA92 also found a discrepancy in red and blue spectral types for ROXs 29, but the difference in spectral type (K4 vs K6) was barely significant, and we do not consider this star a bona-fide composite spectrum object.

BA92 put forward two suggestions for the origin of the composite spectra.

- The systems are close binaries, with components of different temperatures.
- The systems consist of cool stars surrounded by accretion discs. The blue spectral region is dominated by luminosity either from the accretion itself, or from hot spots arising where the accretion stream hits the star.

However, they were unable to determine which, if either, of these explanations was the case. The binary hypothesis was examined by Koresko (1993), who performed speckle interferometry for ROXs 21 (SR 12), ROXs 47a (Do-Ar 51) and ROXs 3. He found that ROXs 21 and ROXs 47a were close binary stars with brightness ratios at 1.65 and 0.33 respectively. However, he also found that coeval binaries could not be responsible for the composite spectra effect. The problem arises as the two components must have comparable luminosities at 5550Å. The cool component must then be larger than the hot component, implying that the hot component is substantially older than the cool component.

Hence, the nature of the objects discovered in BA92 remains a mystery. In order to resolve this mystery, we revisited the objects, more than twenty years later, with medium-resolution spectroscopy in the blue and red regions. The spectra of all four objects show significant changes since the observations of BA92. All objects now show strong Hα emission and a diminished composite spectrum effect. The presence of such variability strongly argues against a binary origin for the phenomenon. Here we suggest that the composite spectrum phenomenon, and the variability witnessed, is caused by changes in the accretion state of the young stars.

Section 2 describes the observations taken, whilst the results are shown in section 3. In section 4 we outline the scheme we propose to explain these results, and discuss its consequences and in section 5 we summarise our conclusions.

2 OBSERVATIONS

On the nights of 2002 Jan 27 and 28 we obtained 5960–7640Å spectra of ROXs 21, ROXs 47a, ROXs 2 and ROXs 3 using the RGO spectrograph on the Anglo-Australian Telescope (AAT) at Siding Spring, Australia. The 1200R grating, blaze-to-camera, in conjunction with the MITTL chip gave a resolution of 1.5Å. The exposure time was 120 secs for each object. The spectra were extracted using the optimal extraction algorithms in figaro (Cohen 1988). Observations of the A-type star SAO184424 were used to correct the spectra for telluric features. Regular observations of arc and flatfield frames were used to calibrate the data.

In addition, on the nights of 2002 August 30 and 2002 September 1, we obtained 3770–4890Å spectra of a sample of 23 of the 30 pre-main sequence objects observed by BA92 using the 2dF spectrograph on the AAT (Lewis et al. 2002). Included in the sample were the four composite spectra objects. Each spectrum consists of 5×300 sec exposures. The data were taken in service mode by E. Corbett. The 1200B grating was used, giving a resolution of 2.2Å. Arc and flatfield frames were obtained after each target exposure, along with offset sky frames (which may be used to calibrate fibre throughput). The data were reduced using the 2dfdr data reduction package, with default settings (Lewis et al. 2002).

3 RESULTS

Figure 1 shows the 3770–4890Å spectra of ROXs 21, ROXs 47a, ROXs 2 and ROXs 3. Shown for comparison in Figure 2 are the original data from BA92. The variability is striking. First, whilst the later spectra of all four objects are characterised by emission lines of the Balmer series and CaII, the original data show no Balmer emission, and strong, broad CaII absorption. Only one object (ROXs 21) shows any sign of CaII or Balmer emission in the earlier data. In all cases, the increase in emission line strength is significant and striking, even when our data are degraded to the resolution and signal to noise of the BA92 spectra. Second, and most intriguing, the prominent G-band seen in the original data at around 4300Å is much weaker in the current data. The G-band is visible in dwarfs from mid-F to late-K type, and peaks in strength around G5V.

With the weakening of the G-band, it is clear that the spectral type inferred from the blue spectral region is later in our data than in the data of BA92. In fact, BA92, used the continuum shape and G-band strength to infer spectral types of K2V–K4V for these objects. Comparison of our spectra and the K7/M0V spectrum in Figure 2 shows that the spectral type inferred from the blue spectral region is...
Figure 2. The original spectra of the BA92 objects, obtained between 1983 and 1986. The spectra have been normalised, and an offset has been applied to the y-axis of the spectra for clarity. Also shown is the spectrum of a K4 dwarf (bottom) and a K7/M0 dwarf (top).

Figure 3. RGO red spectra of the BA92 objects, obtained in January 2002. The spectra have been normalised and an offset has been applied to the y-axis of the spectra for clarity. Now closer to late-K or early M. The implications of this are discussed in section 4.

The red spectral region has also seen significant changes since the original data were taken. BA92 classified all four objects as weak T-Tauri stars on the basis of their Hα emission. Figure 3 shows our recent AAT spectra. A glance at this figure shows that the Hα emission properties of the objects has changed markedly: the red spectra of all four objects are now dominated by strong Hα emission. Table 1 shows the changes in Hα equivalent width between the two observations. In all cases the equivalent width of Hα emission has dramatically increased. The change is large enough such that all four objects would now be classified as classical T Tauri stars, on the basis of their Hα emission. The Hα emission is also very broad. White & Basri (2003) show that the Hα line widths at 10% of peak intensity are often a better indicator of ongoing accretion than Hα equivalent width. They suggest that stars with 10% widths of > 270 km s⁻¹ are accreting, regardless of spectral type. All four objects show 10% widths significantly in excess of this value (see Table 1).

Despite the change in Hα emission properties, the spectral type inferred from the red spectral region remains unchanged with respect to that found by BA92. This removes any uncertainty that the objects we observed are the same objects observed by BA92. We now discuss the implications of these results.

Table 1. Hα equivalent width variations between this paper and BA92. Also shown is the Hα full-width at 10% of maximum intensity for our data, and the spectral types inferred by BA92. The first entry is the spectral type inferred from the region bluwards of Hβ, the second entry is the spectral type inferred from the region around Hα.

| Object    | BA92 | This paper | This paper | BA92 |
|-----------|------|------------|------------|------|
|           | EW (Å) | FW10% (km s⁻¹) | Sp Type    | |
| ROXs 21   | 4.5   | 370±30     | K4/M2.5V   | |
| ROXs 47a  | 9.2   | 460±30     | K2/K7-M0V  | |
| ROXs 2    | 2.8   | 550±30     | K3/M0V     | |
| ROXs 3    | 2.3   | 500±30     | K3/M0V     | |

Considering these facts, we can reject binarity as a cause for composite spectra; it is unlikely that the spectral type of a star can change by several subclasses in <∼ 20 years. A second possibility is that the composite spectra are caused by cool starspots on the surface of a hot young star. This, too, seems unlikely. On a spot-covered star, the overall light is normally dominated by the hot, bright, spot-free photosphere. BA92 calculated that to produce the composite spectrum effect observed required 93% spot coverage. Given that the spectrum in the blue region has also now cooled, starspots would now have to cover the entire star to explain the observed changes.

4 DISCUSSION

4.1 The nature of composite spectra

Any theory which seeks to explain the composite spectra observed in these stars must explain these key facts.

- A composite spectrum always shows a hot spectral type in the blue, and a cooler spectral type in the red.
- The phenomenon is transitory, and decays on a timescales of less than or of the order 20 years.
- Coupled with the disappearance of the composite spectrum, is the emergence of an emission line spectrum from CaII and the Balmer lines in the blue region, and a dramatic rise in the equivalent width of Hα emission in the red region.

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The most promising scheme is that the composite spectra are caused by accretion. In this scheme the source for the hot, blue component is the accretion luminosity itself. Unlike the veiling luminosity typically seen in CTTS, which is featureless and fills in stellar absorption lines, we are suggesting that the accretion luminosity, arising from optically thick accretion columns or in hot spots on the stellar surface, itself exhibits hot spectral features, like the G-band at 4300Å. The stellar spectrum is then completely hidden by this accretion luminosity. An optically thick accretion flow would explain the absence of strong Hα emission in this phase. An attractive property of the accretion model is that the observed spectral changes are easily understood as a fall in the accretion rate. First we consider the blue spectral region. As the accretion rate drops, the accretion flow becomes optically thick, and the luminosity of the flow reduces drastically. The hot spectral features will naturally disappear at this point. The drop in accretion luminosity explains the change to a red continuum, and emergence of an emission line spectrum as the veiling caused by the luminosity disappears. In the red spectral region, the observed changes are simpler, because this region is relatively unaffected by the accretion emission. In this case, the main observed change is a rise in the strength of Hα emission as the accretion columns become optically thin.

This behaviour is not without precedent. Dwarf novae are binary stars consisting of a low-mass red star transferring mass, via an accretion disc to a white dwarf companion. They exhibit frequent outbursts, which are linked to an instability in the accretion disc which causes sudden increases in accretion rate. These objects are characterised in their quiescent state by a strong emission line spectrum. During outburst, however, high accretion rates mean the disc atmosphere becomes optically thick, and an absorption line spectrum, arising from the disc photosphere, is observed (e.g. Mansperger & Kaitchuck 1990). The similarities between this behaviour and the behaviour seen in the BA92 objects are striking.

The most obvious implication of this explanation is that here are four stars which may exhibit high accretion rates in the WTT phase. If the blue luminosity in the BA92 objects is dominated by accretion power, we can calculate the required accretion rates from the observed B and V magnitudes, after correction for reddening. We assume the accretion emission is a black body, with its temperature of 5200K taken to correct for reddening. We assume the accretion emission. In this case, the main observed change is a rise in the strength of Hα emission as the accretion columns become optically thin.

4.2 Near-infrared excesses

It is pertinent to consider if there is other evidence for the existence of accretion discs in these stars. Circumstellar discs can produce strong infrared emission significantly in excess of the stellar luminosity. Such excess infrared emission is easily detected in a near-infrared colour-colour diagram (see Haush et al. 2001, for example). We collated JHK photometry for the composite spectrum stars from a number of sources (Bouvier & Appenzeller 1992, Walter et al. 1994, Rydgren et al. 1976, Cutri et al. 2003, Jensen & Mathieu 1994). The data were transformed to the UKIRT photometric system using the transformations in Carpenter (2001) and an average of each magnitude was taken. None of the four stars showed any evidence for a near infrared excess when placed on a JHK colour-colour diagram. L band photometry was also available for ROXs 47a and 21. JHKL colour-colour diagrams are a much more sensitive disc indicator than JHK diagrams, often revealing evidence for circumstellar discs in objects showing no JHK excess (see Haush et al. 2001, for example). In this case, ROXs 47a showed a K-L excess of a few tenths of a magnitude, whilst ROXs 21 showed no K-L excess. The K-L excess in ROXs 47a may, however, be due to a low-mass companion (Simon et al. 1987). Furthermore, we caution about over-interpretation of these data; T Tauri stars are intrinsically variable in the near infrared, with variability up to 1 magnitude not uncommon (Eiroa et al. 2002). As the photometry obtained above was not obtained simultaneously it seems plausible that variability could mask any near infrared excess present.

Although there is a strong correlation between near-infrared excess and other disc indicators, the absence of a near infrared excess does not necessarily imply the absence of an accretion disc. For example, Rebull et al. (2002) found several stars with very strong Hα emission, presumably arising in accretion columns, which exhibited no near infrared excesses. This presumably means it is possible to maintain significant accretion rates onto a young star through a disc which is optically thin in its inner parts.

4.3 Time-dependant behaviour of the composite spectrum state.

To better understand the physics of what might cause changes in accretion rate it is pertinent to consider the time-dependence of these changes. For example, how long does the high accretion state last? Is the transition between high and low states short?

The BA92 sample consists of 30 X-ray selected pre-main sequence stars which also exceed a given optical flux limit. In their sample, 4 out of 30 objects show a composite spectrum effect. Naively, this suggests that ~10% of T Tauri stars are our value of 10^{-7} M_⊙ yr^{-1} is only a rough estimate, it is certainly true that the composite spectrum objects were accreting at a rate comparable to that seen in CTTS. This would be a startling reversal of the paradigm in which strong Hα emission is taken as evidence of strong accretion onto the young star, and weak Hα emission denotes a non-accreting source.
in such a state (but see below). Twenty years later, our 2dF spectroscopy shows that all four objects are now in a low accretion rate state - this argues that the high state is likely to last less than 20 years, with long-duration high states of 50 years or more being very unlikely. Furthermore, in the study of BA92, the composite spectrum effect was either absent or showed similar amounts of spectral type mismatch in all objects. In other words, no objects were observed in a transition between high and low states. This then implies that the transition time between the two states is short - statistical arguments suggest the transition time is unlikely to be longer than 0.5 years.

The timescale of 0.5 years is interesting because it suggests a physical mechanism for the change in accretion state. In dwarf novae, the cause of the accretion rate variations is a thermal-viscous instability (see Lasota (2001) for a review). A similar thermal-viscous instability is believed to cause the FU Orionis phenomena in young stars. In dwarf novae, the accretion rate changes on the thermal timescale for the disc. The thermal timescale for the inner region of T Tauri discs is roughly half a year (at a radius of 0.1 AU). This suggests a thermal-viscous instability in the inner disc may be responsible for the change in accretion rates between the two states.

Interestingly, none of the nineteen other objects we observed from the BA92 sample underwent a change from a low to a high state - the spectral type inferred from our 2dF spectra agreed with the classification of BA92, with the exception of the four composite spectrum objects\(^1\). In other words, the sample of BA92 contained four high state objects and no low state objects. Although we have observed four high-low transitions, no low-high transitions have occurred within the BA92 sample. This suggests that the sample of BA92 was strongly biased towards objects which were in a high state at the time of their observations, and that in fact the fraction of objects in a high state at any given time may be much lower than 10%. Only simultaneous blue/red spectroscopy of an unbiased sample of pre-main sequence stars can resolve this question.

### 4.4 \(\text{H}\alpha\) variability in T Tauri stars

We note here that this is not the first evidence for large changes in \(\text{H}\alpha\) emission strength in T Tauri stars. For example, Joergens et al. (2001) noted that the equivalent width of \(\text{H}\alpha\) emission in the T Tauri star RX J1608.6-3922 varied from 7-14\(\AA\). Herbig (1998) noted that several of the young stars in the cluster IC 348 showed variable \(\text{H}\alpha\) emission, with some objects changing from 2\(\AA\) to >10\(\AA\) in equivalent width. In \(\lambda\)-Ori, the survey of Duerr et al. (1982) catalogued 82 stars with \(\text{H}\alpha\) emission, which they categorised as “strong”, “medium” and “weak”. The region was revisited by Dolan & Mathieu (2001), who found that the \(\text{H}\alpha\) equivalent widths of the “strong” sample included lines as weak as 6\(\AA\), a fact they attribute to variability. Then there is the remarkable case of KH 15D - a weak T Tauri star which shows

\(^1\) ROXs 4 did show a discrepancy with the BA92 spectral type of K4 being incompatible with our classification as early-M, however close inspection of the spectrum published in BA92 leads us to conclude that this star was mis-classified by the authors.

4.5 The link between \(\text{H}\alpha\) and discs in T Tauri stars

It seems certain that strong (EW > 10 \(\AA\)) \(\text{H}\alpha\) emission is indicative of the presence of active accretion and hence, an accretion disc. Chromospheric emission from \(\text{H}\alpha\) rarely rises above 10\(\AA\) (Martin 1997), so an additional source of \(\text{H}\alpha\) emission must be found. Furthermore, in stars with \(\text{H}\alpha\) emission of EW > 10\(\AA\), the strength of \(\text{H}\alpha\) emission is proportional to the B-V excess (e.g. Herbig 1998). T Tauri stars with strong \(\text{H}\alpha\) also show the infrared excesses thought to arise from the inner accretion disc (Cabrit et al. 1990).

However, it seems that the conclusion that WTTs lack discs is not correct. In fact, it seems certain that at least some WTTs do possess discs. For example, in the case of KH 15D, which is a WTTs, it is material in a circumstellar disc that is believed to be responsible for eclipses in this system (Herbst et al. 2002). Bary et al. (2002) detect molecular hydrogen, believed to originate in an accretion disc, again around a WTTs. Also, the variability of \(\text{H}\alpha\) emission on timescales as short as twenty years argues against its usefulness as a disc indicator (it is unlikely that the discs themselves could be coming and going on these timescales). Furthermore, in a sample of 27 WTTs, Gregorio-Hetem & Hetem (2002) find that 60% of the objects show infrared excesses which indicate a circumstellar disc.

In at least some of these cases it is tempting to explain the failure of the accepted paradigm by stating that WTTs may or may not have discs, but that these discs are currently not accreting onto the central star. If our interpretation of the composite spectrum phenomenon is correct, however, we are forced to accept that not only are some WTTs accreting, but they are accreting at rates higher than, or comparable to most CTTs.

The presence of active accretion discs amongst the WTTs population is an important result. It suggests that there is no fundamental difference between CTTs and some WTTs, other than the current accretion rate. This might explain, amongst other things, why an evolutionary link between CTTs and WTTs has been difficult to establish. Furthermore, if the time-averaged accretion rate in T Tauri stars is higher than previously suspected, this might explain age spreads seen in some star forming regions. An accretion rate of 10\(^{-7}\)M\(_\odot\)yr\(^{-1}\), as seen in the BA92 objects is high enough to upset the thermal balance of a T Tauri star, moving it back towards the birthline in a HR diagram (Tout et al. 1999).
5 CONCLUSIONS

We have obtained new spectra of the objects found to exhibit composite spectra by Bouvier & Appenzeller (1992). The composite spectrum effect has diminished in the intervening years; the blue spectral type now agrees more closely with that inferred from the red spectral region. In addition, a series of emission lines has appeared, and the equivalent width of $\text{H}_\alpha$ emission has risen drastically. These spectral changes can be understood if the composite spectrum effect is a result of the blue spectrum being dominated by hot, optically thick emission from the accretion flow. The luminosity in the blue then implies accretion rates of $10^{-7}\,\text{M}_\odot\,\text{yr}^{-1}$. An important result of this explanation is that the paradigm relating $\text{H}_\alpha$ emission to accretion discs is incomplete; at least some WTTs both possess accretion discs, and are accreting from them at a high rate.

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