DRAFT VERSION FEBRUARY 2, 2008
Preprint typeset using LaTeX style emulateapj v. 6/22/04

A LONG-LIVED ACCRETION DISK AROUND A LITHIUM-DEPLETED BINARY T TAURI STAR

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Draft version February 2, 2008

ABSTRACT

We present a high dispersion optical spectrum of St 34 and identify the system as a spectroscopic binary with components of similar luminosity and temperature (both M3±0.5). Based on kinematics, signatures of accretion, and location on an H-R diagram, we conclude that St 34 is a classical T Tauri star belonging to the Taurus-Auriga T Association. Surprisingly, however, neither component of the binary shows Li I 6708 Å absorption, the most universally accepted criterion for establishing stellar youth. In this uniquely known instance, the accretion disk appears to have survived longer than the lithium depletion timescale. We speculate that the long-lived accretion disk is a consequence of the sub-AU separation companion tidally inhibiting, though not preventing, circumstellar accretion. Comparisons with pre-main sequence evolutionary models imply, for each component of St 34, a mass of 0.37 ± 0.08 $M_{\odot}$ and an isochronal age of 8 ± 3 Myr, which is much younger than the predicted lithium depletion timescale of ~ 25 Myr. Although a distance 38% closer than that of Taurus-Auriga or a hotter temperature scale could reconcile this discrepancy at 21-25 Myr, similar discrepancies in other systems and the implications of an extremely old accreting Taurus-Auriga member suggest instead a possible problem with evolutionary models. Regardless, the older age implied by St 34's depleted lithium abundance is the first compelling evidence for a substantial age spread in this region. Additionally, since St 34's coeval co-members with early M spectral types would likewise fail the lithium test for youth, current membership lists may be incomplete.

Subject headings: stars: pre-main sequence — stars: abundances — binaries: spectroscopic

1. INTRODUCTION

T Tauri stars are a class of young ($\lesssim$ 1-10 Myr) low mass ($\sim 0.1 - 2$ $M_{\odot}$) stars. Those which show signatures of accretion from a circumstellar disk, such as optical veiling and/or strong emission lines (e.g. Hα) are called classical T Tauri stars while those without accretion signatures are called weak-lined T Tauri stars. Observational studies of these stars have provided the foundation upon which current theories of star and planet formation are based.

Initial efforts to find T Tauri stars primarily relied on objective-prism imaging surveys of dark clouds in search of strong emission line stars (e.g. Joy 1949). This technique, while relatively effective, biased the discovered populations by mostly identifying classical T Tauri stars. Subsequent surveys that focused on proper motion (e.g. Jones & Herbig 1979; Hartmann et al. 1991), infrared excesses (e.g. Kenyon et al. 1990), coronal/choromospheric indicators of youth such as x-ray emission (e.g. Walter et al. 1988; Wichmann et al. 1996) and Ca II H&K emission (e.g. Herbig et al. 1986), or location on an H-R diagram (e.g. Briceño et al. 1998), helped to establish a more complete and less biased census of star forming regions (most notably, Taurus-Auriga). However, since some older binary star systems (e.g. RS CVn type stars) and post-main sequence stars (e.g. AGB stars) also exhibit many of these same properties, confirmation of T Tauri status (i.e. extreme youth) has usually necessitated measurement of the surface abundance of ^{7}Li. During the pre-main sequence (PMS) contraction of a young star, ^{7}Li is destroyed via p,α reactions in the stellar interior when the central temperature rises above $\sim 3 \times 10^6$ K (Bodenheimer 1965). Because of rapid mixing in fully convective low mass T Tauri stars, lithium is completely depleted in a small fraction of the contraction timescale (D'Antona & Mazzitelli 1994; Bildsten et al. 1997; Baraffe et al. 1998; Burke et al. 2004). The presence of the strong, easily observable Li I 6708 Å absorption feature therefore implies that the star must be very young. The depletion timescale is a strong function of mass, however, being quickest ($\sim$ 20 Myr) for stars of mass ~ 0.6 $M_{\odot}$. The onset of a radiative core, which inhibits efficient mixing, prior to full lithium depletion in higher mass stars delays their depletion timescale. The cooler central temperatures of lower mass stars likewise delays their depletion timescale; lithium-burning temperatures are never reaches for substellar objects with M $\lesssim 0.06$ $M_{\odot}$. Thus at the highest and lowest T Tauri star masses, other diagnostics are needed to confirm a star's extreme youth.

Here we present high-dispersion spectroscopic observations of St 34 (HBC 425; RA: 04 54 23.7, DEC: +17 09 54, J2000; V= 14.4 mag), discovered as a strong Hα emission line star in the objective prism survey of Stephenson (1986) and later shown to be an early- to mid-M star (Downes & Keyes 1988). Because of its strong Hα emission and location, it has been assumed to be a member of the Taurus-Auriga T Association (Kenyon & Hartmann 1995). Our new measurements demonstrate that St 34 is a spectroscopic binary, a classical T Tauri star, and strengthen the case for its association with Taurus-Auriga. Unlike all other classical T Tauri stars and known members of Taurus-Auriga, however, St 34 has depleted its lithium. These results are used to assess the validity of evolutionary model predictions, the possibility of a lithium-depleted population in Taurus-Auriga, and the influence of sub-AU separation companions on circumstellar disk lifetimes.

2. SPECTROSCOPIC OBSERVATIONS AND INFERRED PROPERTIES

The W. M. Keck I 10-m telescope and High-Resolution Echelle Spectrometer (Vogt et al. 1994) were used on 2003 Feb 17 to obtain a high dispersion (R $\approx$ 34,000) optical spectrum (6330-8750 Å) of St 34. The observational

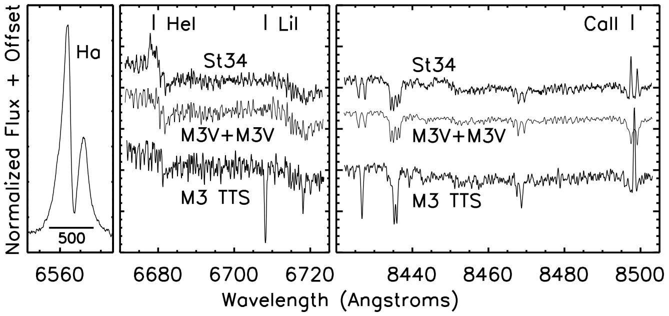

FIG. 1.— Portions of the Keck/HIRES spectrum of St 34 showing the strong, broad Hα emission profile (*left panel*) and 2 temperature sensitive regions (*right panels*); the wavelength scales are the same in all panels. The bar under the the Hα profile indicates a velocity width of 500 km/s. A synthetic spectroscopic binary, composed of 2 M3 dwarf stars, and the M3 weak-lined T Tauri star TWA 8a are also shown for comparison. St 34 shows no lithium in its spectrum.

TABLE 1

	system	primary	secondary
Obs. Julian Date	2452688.85	$\cdots$	$\cdots$
EW[Hα] (Å)	-51.6	$\cdots$	$\cdots$
Hα 10%-width (km/s)	512	$\cdots$	$\cdots$
EW[Li I] (Å)	$\cdots$	< 0.06	< 0.06
$v\sin i$ (km/s)	$\cdots$	< 7.2	< 7.0
Radial Velocity (km/s)	17.9 ± 0.6	47.1 ± 0.4	-11.3 ± 0.4
Spectral Type	$\cdots$	M3±0.5	M3±0.5
$[F_{prim}/F_{sec}]_{6500}$	1.10 ± 0.04	$\cdots$	$\cdots$
r_{6500}	0.13 ± 0.04	$\cdots$	$\cdots$
$[F_{prim}/F_{sec}]_{8400}$	0.99 ± 0.07	$\cdots$	$\cdots$
r_{8400}	< 0.09	$\cdots$	$\cdots$
Mass ($M_\odot$)	$\cdots$	0.37±0.08	0.37±0.08
Isochronal Age (Myr)	$\cdots$	8±3	8±3
Lithium Depletion Age (Myr)	$\cdots$	> 25	> 25

NOTE. — The systemic radial velocity is the average of the components. Its uncertainty does not reflect the uncertainties in their masses.

setup, spectral calibration and extraction are as described in White & Hillenbrand (2004). Portions of the resulting spectrum of St 34 are shown in Figure 1. Its most distinguishing characteristics are strong, broad Hα emission, double-lined photospheric features (implying binarity), and no Li I 6708 Å absorption. A Li I equivalent width upper limit of 0.06 Å for each spectroscopic component is determined by the size of features in the psuedo-continuum.

The stellar properties of St 34 are determined from analysis of each component's spectral features[1]. The procedure is described in White & Hillenbrand (2004), but is tailored here for the analysis of a spectroscopic binary. Visual inspection of St 34's spectrum reveals that the two components are of similar brightness, well separated in velocity, and slowly rotating. This allows a more independent analysis of each component. Radial velocities and $v\sin i$ values are measured by fitting the 2 peaks of the cross-correlation function determined using non-rotating early- and mid-M dwarf templates. Each component's spectral type, the system flux ratio, and the continuum excess (or veiling, defined as $r = F_{excess}/(F_{prim}+F_{sec})$) are determined simultaneously by comparisons with synthetic spectroscopic binaries, generated by combining dwarf standards at the appropriate radial and rotational velocities. For the synthetic spectra, the spectral type of each component is allowed to vary from M0 to M5, the flux ratio from 0.5 to 2.0, and the continuum excess from 0.0 to 2.0. The best fit is determined by minimizing rms differences between St 34 and a synthetic binary spectrum over several temperature sensitive regions (see White & Hillenbrand 2004, for details). The components have the same spectral type (both M3±0.5) and are of similar brightness. The primary is assumed to be the star that is slightly (10±4%) brighter at 6500 Å. Although the composite St 34 system appears to have a small amount of continuum excess at 6500 Å ($r_{6500} = 0.13 \pm 0.05$), it is not possible to tell if this excess is associated with only one or both of the components. No continuum excess is detected at longer wavelengths ($r_{8400} < 0.09$). Weak, narrow He I 6678 Å and Ca II 8498, 8662 Å emission is observed (Figure 1), but no forbidden line emission (e.g. EW [SII] 6716, 6731 Å < 0.05 Å). Table 1 summarizes the spectroscopic properties of St 34.

3. EVIDENCE FOR ADOLESCENCE

The Hα emission line profile of St 34 is both strong (equivalent width = -51.6 Å) and broad (full-width at 10% of the peak = 512 km/s). The breadth of this feature is not a consequence of binarity; the two peaks in the profile are separated in velocity by $\sim$ 180 km/s, which is much greater than the velocity separation of the components (58.4 km/s). Although some late-type main sequence stars also display Hα emission, caused by flares and other chromospheric activity, this emission is less intense and less broad than the profile of St 34 or any accreting young star (e.g. White & Basri 2003). Chromospherically active main-sequence stars also tend to be rapidly rotating and X-ray bright, in contrast to the small $v\sin i$ values and X-ray non-detection of St 34 (via ROSAT; König et al. 2001). Moreover, the observed strength of the Hα emission is similar to that seen in previous low spectral resolution observations of St 34 (EW= -78 Å; Downes & Keyes 1988; Kenyon & Hartmann 1995), suggesting the current epoch was not a transient flare-like event. The Hα emission line profile of St 34, in light of its stellar properties, is most consistent with originating from a high velocity accretion flow (e.g. Muzerolle et al. 2000). The low level continuum excess at 6500 Å supports the interpretation that one or both components of the binary are accreting, though the accretion rate is low (2.5×10^{-10} $M_\odot$/yr, following a prescription similar to White & Hillenbrand 2004). Based on this evidence for accretion, we conclude that St 34 is a classical T Tauri star.

The reservoir of accreting material has not yet been detected, however. St 34 has no measurable near-infrared (K_s) excess, based on comparing the observed K_s magnitude to that predicted from the spectral type, extinction (determined below), and J magnitude. Although Weaver & Jones (1992) claim St 34 was detected by IRAS at 12μm, 25μm, and 60μm, inspection of the IRAS Sky Survey Atlas, even after the more up-to-date HiRes processing, reveals no point- or extended-source within several arcminutes of St 34. We suggest the Weaver & Jones (1992) identification was spurious. St 34 was also not detected in the 1.3-mm survey by Osterloh & Beckwith (1995, $F_{1.3mm} < 15$ mJy), which is sensitive to cool outer disk material. We emphasize, however, that the lack of detected excess emission is consistent with

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[1] High spatial resolution imaging has identified a star at $1\farcs2$ distance from St 34, possibly making the system a hierarchical triple (White et al. 2004). This candidate companion is much fainter than the primary pair at 2.2 μm (ΔK = 2.5 mag), and thus unlikely to contaminate the optical spectrum.

St 34's low level accretion and cool stellar temperature; several low mass accreting stars in Taurus-Auriga have not yet been detected at far-infrared and millimeter wavelengths either (Kenyon & Hartmann 1995).

Kinematic information supports the assertion that St 34 is a member of the Taurus-Auriga T Association. Assuming that the spectroscopic binary components have the same mass, as suggested by their similar spectral type and brightness, the systemic radial velocity is 17.9 ± 0.6 km/s, which is identical to the mean of Taurus members (17.8 km/s; Hartmann et al. 1986). St 34 has a proper motion of $\mu_\alpha = +1.8 \pm 3.5$ mas/yr and $\mu_\delta = -12.6 \pm 3.5$ mas/yr, which, in combination with its radial velocity and an assumed distance of 145±10 pc, corresponds to space motion of $U = -15.6 \pm 1.5, V = -8.4 \pm 2.2, W = -8.8 \pm 2.3$ km/s (E. Mamajek, priv. comm.). This motion is statistically most consistent with that of lithium-rich Taurus members (e.g. Jones & Herbig 1979) as opposed to nearby moving groups (e.g. β Pictoris; Zuckerman & Song 2004). Thus, based on evidence for extreme youth, spatial proximity (within 1.5° of L1558), and space motion, we conclude St 34 is a member of the Taurus-Auriga T Association.

Mass and age estimates for St 34 are determined by comparing the temperature and luminosity with the Baraffe et al. (1998) PMS evolutionary models. A temperature of 3415° K is assigned using the spectral type - temperature scale of Luhman et al. (2003), which is slightly hotter than a typical dwarf temperature scale, but yields coeval cluster populations in combination with this evolutionary model. A visual extinction of 0.24 mag is determined by comparing the $J-H$ color to that expected for an M3 star (Kirkpatrick & McCarthy 1994), using a standard interstellar extinction law (Rieke & Lebofsky 1985). The 2MASS magnitudes of St 34 are $J = 10.69 \pm 0.02$, $H = 10.08 \pm 0.02$, and $K_s = 9.79 \pm 0.02$; no reliable optical colors are available. Luminosity is computed by applying a bolometric correction of +1.75 to the reddening corrected J magnitude, which is split assuming equal contribution from each component of the binary. A distance of 145±10 pc, corresponding to that of Taurus (Bertout et al. 1999), yields $\log(L/L_\odot) = -1.03 \pm 0.06$ for each component. In the top panel of Figure 2, St 34 is shown on an H-R diagram along with the Baraffe et al. (1998) evolutionary models. For each component, the implied age is 8 ± 3 Myr and mass is 0.37 ± 0.08 $M_\odot$. St 34 appears to be somewhat older than most stars in Taurus, which have an average age of 2-3 Myr (White & Ghez 2001) and are all thought to be younger than 4 Myrs (Hartmann 2003).

In the bottom panel of Figure 2, the lithium abundance of St 34 is compared to the lithium depletion predictions of the same Baraffe et al. (1998) evolutionary models. The Li 6708 Å equivalent width of $\lesssim 0.06$ Å corresponds to a lithium abundance of $\log n(\mathrm{Li}) \lesssim 0.3$ dex, following the curves of growth shown in Song et al. (2002, Figure 2). This amount of depletion implies an age $\gtrsim 25$ Myr. Comparisons with other evolutionary models yield lithium depletion ages that agree to within 20% (see e.g. Burke et al. 2004).

4. DISCUSSION AND IMPLICATIONS

4.1. *A Possible Problem for Lithium Depletion Predictions*

Although the isochronal age inferred for St 34 is much younger than its lithium depletion age, a distance of 90 pc instead of the assumed 145 pc would increase the isochronal age to 25 Myr, consistent with the lithium depletion age. Similarly, if the assumed temperature is increased to 3600° K (which is 340° K hotter than a typical M3 dwarf temperature), the isochrone and lithium depletion ages agree at 21 Myr. At an age $\gtrsim 20$ Myrs, however, St 34 would be by far the oldest classical T Tauri star known; MP Mus in Scorpius-Centaurus (age ~ 13 Myr; Mamajek 2002) is currently thought to be one of the oldest. St 34 would also be older than typical cloud dispersal timescales ($< 10-20$ Myr; Palla & Galli 1997), which would call into question its association with Taurus-Auriga as location and kinematics suggest. This large age for St 34 seems unlikely. Song et al. (2002) identified a similar discrepancy between isochronal and lithium depletion ages in the case of HIP 112312 A. The low lithium abundance of this M4 star implies an age $\gtrsim 35$ Myr, while its isochronal age, which is based on a Hipparcos determined distance, is 6 ± 3 Myrs (Figure 2). As with St 34, a hotter temperature could reconcile these ages at 20-25 Myr. Finally, we note that the lithium depletion ages of young open clusters, including the Pleiades, α Persei, IC 2391, and NGC 2547 (Burke et al. 2004), are all systematically larger than the isochronal ages fitted to both low mass unevolved members and the upper main sequence near the nuclear turn-off (Stauffer et al. 2001; Jeffries & Naylor 2001). Overall, the emerging observational evidence suggests a problem with lithium depletion ages, being systematically too old, though a problem with the pre-main sequence temperature scale, being too cool, can not be ruled out.

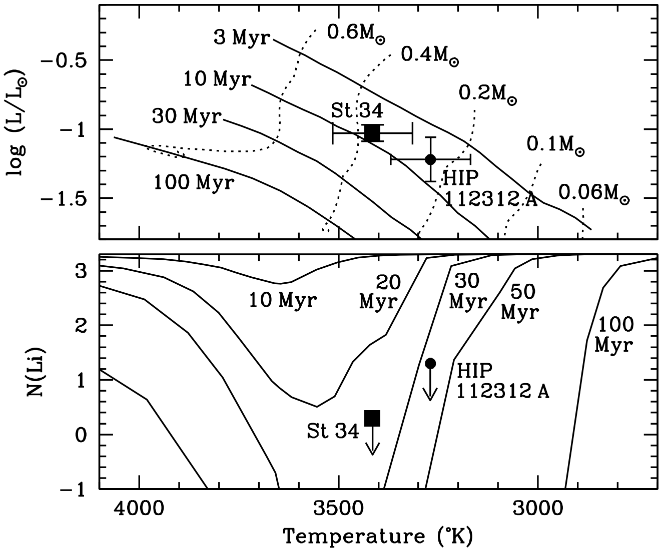

FIG. 2.— In the top panel, St 34 (*square*) and HIP 112312 A (*circle*) are shown on an H-R diagram along with the evolutionary models of Baraffe et al. (1998). Since both components of St 34 have the same temperature and luminosity, only 1 point is visible. In the bottom panel St 34 and HIP 112312 A are shown on a lithium abundance versus temperature diagram, along with the isochrones predicted by the same Baraffe et al. (1998) models. Although the location of St 34 and HIP 112312 A on the H-R diagram suggests ages $\lesssim 10$ million years, the depleted lithium abundance of both stars suggests ages older than ~ 25 Myr and ~ 35 Myr, respectively.

4.2. *Implications for the Taurus Population*

If St 34 is a member of the Taurus-Auriga T Association, as evidence suggests, it presents the first strong case for a significant age spread in this region. St 34 must be older than currently forming stars by an amount equal to the lithium depletion timescale. Evolutionary models suggest this could be as large as 21-25 Myr, but as noted above, these values appear to be extreme. The age spread would be more accurately constrained if additional older, possibly lithium depleted members are discovered. St 34 was easily identified because of its strong Hα emission. Lithium depleted weak-lined T Tauri stars, on the other hand, even if identified and observed spectroscopically, would have thus far been dismissed as non-members. In order to estimate how many older weak-lined systems there could be in Taurus, we use the ratio of weak-lined to classical T Tauri stars in clusters of age $\sim$ 10 Myr, which range from $\sim$ 90% for the TW Hydrae Association (age $\sim$ 8 Myr; Zuckerman & Song 2004) to $\sim$ 99% for the Sco-Cen subgroups (age $\sim$ 13 Myr; Mamajek 2002). If surveys of these clusters are also biased by requiring the presence of lithium absorption for a member to be confirmed, these ratios could be even higher. This suggests that St 34 may have 10 and possibly many 10s of coeval co-members that are weak-lined T Tauri stars. Those of early-M spectral type will have likely depleted their lithium (Figure 2). Current membership lists of Taurus may therefore be incomplete.

The Einstein and ROSAT surveys may have identified some of these lithium poor stars. Walter et al. (1988) and Wichmann et al. (1996) together identified 17 stars with spectral types M1 - M3.5 in Taurus, nearly half of which have been subsequently dismissed as non-members because of depleted lithium. Some of these lithium-poor stars nevertheless have radial velocities consistent with Taurus (e.g. RX J0446.8+2255; Wichmann et al. 2000), suggesting they could in fact be bona fide members. Confirmation of membership will require more accurate estimates of distance, proper motion, and surface gravity. We note that if this proposed older population is identified, it has significant implications for the duration of star formation in Taurus, which is generally believed to be less than 4 Myr (Hartmann 2003, but see Palla & Stahler 2002), and for the initial mass function of Taurus, which apparently peaks at a mass (~ 0.8 M$_\odot$; Luhman et al. 2003) slightly larger than the mass where lithium depletion occurs first.

4.3. *Long-Lived Accretion Disks in Close Binary Systems*

With an age of $\gtrsim 8$ Myr, St 34 is one of a handful of old ($\gtrsim 10$ Myr) classical T Tauri stars. We speculate than in many cases these long-lived accretion disks are a consequence of a tidally inhibited accretion flow caused by a sub-AU separation companion. The properties of St 34, for example, imply a binary separation of $\lesssim 0.78$ AU. As has been identified in some spectroscopic binary systems (e.g. DQ Tau; Basri et al. 1997), and predicted by numerical simulations (Artymowicz & Stephen 1996), the orbital dynamics of a close binary does not preclude accretion from a circumbinary disk. Nevertheless, we suggest that it is less efficient. In support of this, there is some evidence for a higher frequency of spectroscopic binaries among old classical T Tauri stars than among younger T Tauri populations, for which the binary fraction is only 7 ± 3% (Mathieu 1994, for periods less than 100 days;). Of the 4 classical T Tauri stars in the TW Hydrae Association, 50% are spectroscopic binaries (TWA 5A, Hen 3-600A; Muzerolle et al. 2000; Mohanty et al. 2003). Of the remaining 2 accreting stars (TW Hya, TWA 14), only TW Hya has multiple high-dispersion measurements sensitive to radial velocity variations, but its pole-on orientation (Weinberger et al. 2002) would significantly inhibit the detection of a close companion in a coplanar orbit. Both TWA 14 and TW Hya could be yet unidentified sub-AU binary systems. A more complete binary census of these and other old accretors (e.g. MP Mus; Mamajek 2002) is needed to confirm this hypothesis. One interesting implication is that planets would have a longer time to form in the circumbinary disk of sub-AU separation binary stars than around single stars.

We thank I. Baraffe, A. Ghez, and J. Stauffer for helpful discussions and are grateful to E. Mamajek for generously providing valuable kinematic information and insight. We appreciate the data provided by the NASA/IPAC Infrared Science Archive and the privilege to observe on the revered summit of Mauna Kea.

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