

Observational Evidence of Transition between Protostellar Objects and T Tauri Stars

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1. Introduction

The distribution of low-mass T Tauri stars in the H-R diagrams shows a definite upper boundary, or “birthline” (Cohen and Kuhi; 1979). Stahler (1983) noted that the H-R diagrams for T Tauri stars in the different star forming regions tend to show the same upper envelope. Shu et al. (1987) pointed out that the star must be able to burn deuterium. He proved that in low-mass protostars, which are still accreting matter, the burning of deuterium keeps the core temperature at about one million degrees. This thermostat effect persists as long as the accretion process continues to supply deuterium. The net result is to keep the protostar’s mass-to-radius ratio constant. Once the process of accretion from their natal cloud onto a star ends, the stars becomes an optically visible object. The first appearance of a star is defined by the “birthline”, the temperature-luminosity boundary indicated by a heavy curve in the H-R diagram (Fig. 1). To the right of the line, an object is collapsing gas cloud onto the core; so called, the “protostar” phase, to the lower-left, is a T Tauri phase believed to be in a state of quasi-static contraction following the end of the collapse.

Thus, the birthline appears to provide the link between the protostars and visible T Tauri stars. In this report, I discuss the observational aspects characterizing the transitional phase; (1) spectral energy distribution, (2) ice absorption features, and (3) polarization throughout the next sections.

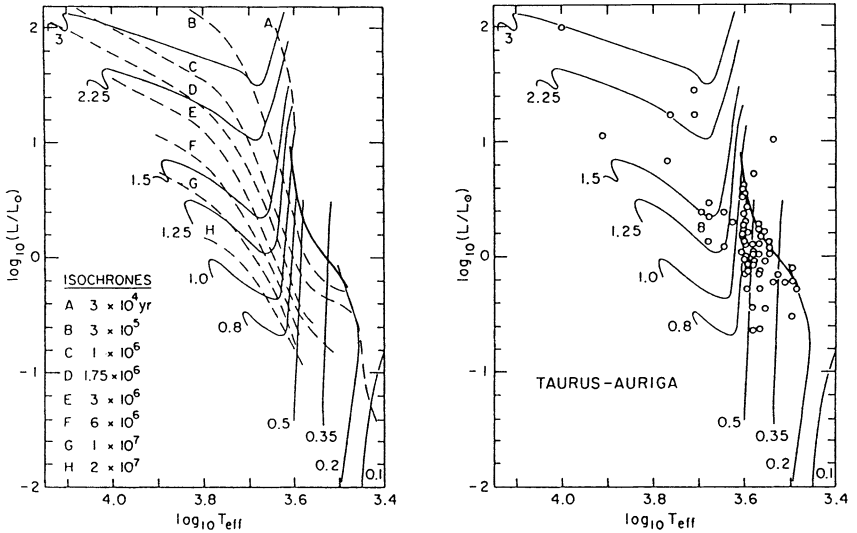


Fig. 1. (left) The theoretical birthline in the Hertzsprung-Russell diagram. The birthline for stars with masses between $0.2 M_{\odot}$ and $1.0 M_{\odot}$ is shown as the heavy solid curve. The lighter solid curves are the Hayashi tracks for the indicated values of mass. The dashed curves are isochrones of Kelvin-Helmholtz age. (right) Comparison of the theoretical birthline (heavy curve) with T Tauri observation on the Taurus-Auriga dark cloud. The circles represent those stars for which Cohen and Kuhi (1979) obtained true bolometric luminosities. Figures are adapted from the papers of Cohen and Kuhi (1979) and Stahler (1983).

2. Spectral energy distribution

Adams *et al.* (1987) suggested that the overall spectral energy distribution corresponds to an evolutionary sequence from protostars to T Tauri stars. In this scheme, Class I sources with a flat or rising spectrum toward the long wavelengths in the $\log \lambda F_{\lambda}$ vs $\log \lambda$ diagram, are deeply embedded sources seen only through the infrared. Class II objects have energy distributions typical of T Tauri stars, displaying a wide range of both ultraviolet and infrared excess. Class III objects, which are often found at the cloud periphery, display blackbody-like energy distributions.

The problem of “overall color-evolution” of YSOs has already been settled in 1980³ by the extensive observations of near infrared photometries from the ground (Myers *et al.*, 1987; Herbig and Bell, 1988) and mid- to far-infrared survey with the Infrared Astronomical Satellite (IRAS) (Beichman

et al., 1986) from protostars to T Tauri stars.

It has been noticed that the birth-line corresponds to the change of colors between Class I and II with evolution of their circumstellar materials. It is of crucial importance to investigate the evolution of circumstellar envelopes in relation to YSOs. We started a near infrared spectrophotometric survey for a number of T Tauri and related objects belonging to Class II and III with a recently commissioned Prism Array SpectroPhotometer (PASP I). The spectral energy distributions in the wavelengths from 0.95 to 2.5 μm were divided into four groups; (a) single Black-Body [BB] with water-vapor, (b) single BB without water-vapor, (c) non-single BB due to superposition of several temperatures, and (d) non-single BB due to H^- ion. Of these four groups, the T Tauri stars belonging to (c) (DY Tau, DG Tau, T Tau, XZ Tau, HN Tau, DR Tau, UY Tau, RW Aur, and SU Aur) with a veiling effect from UV to visual excess, have a large infrared excess which can be explained by the superposition of thermal emission with several temperatures. Because the veiling phenomenon was interpreted to be due to the mass accretion from a circumstellar envelope interacting with a central star (Lynden-Bell and Pringle, 1974), it is likely that these ten stars belong to the youngest of the T Tauri stars, still having a large amount of circumstellar materials.

3. Ice absorption feature

An absorption band of 3.1 μm is a sensitive indicator of environments such as temperatures and/or UV radiation fields in the star-forming regions, because it should evaporate or be destructed by radiation.

Many lines of sight through dense clouds show the absorption feature, which is usually attributed to solid H_2O . This band is found only on the lines of sight that pass through dense, dark regions (Taurus dark cloud, ρ Ophiuchi, R CrA, Serpens dark clouds), in which most of the T Tauri stars show little or no 3 μm feature (Cohen, 1975; Whittet *et al.*, 1988). This is interpreted that gas and dust having already disperse by the mass loss before the star reached a T Tauri star phase.

To investigate the extent of the presence of ice absorption in the evolution from protostars to T Tauri stars, we carried out spectroscopic observation with low-resolution ($R = 160$) in the wavelengths from 2.4 to 3.8

μm of the pre-main sequence stars, including T Tauri stars and protostellar objects in Taurus dark cloud region (Sato *et al.*, 1990), using the Cooled Grating Array Spectrometer (CGAS) on a 3 m IRTF telescope. The ice-band features have been detected in the youngest T Tauri stars as well as in low-mass protostars (Fig. 2). The youngest T Tauri stars have their optical depths of the ice-band, τ_{ice} , between 0.1 to 0.4. It was found that τ_{ice} for the objects in the Taurus dark cloud decreases progressively from

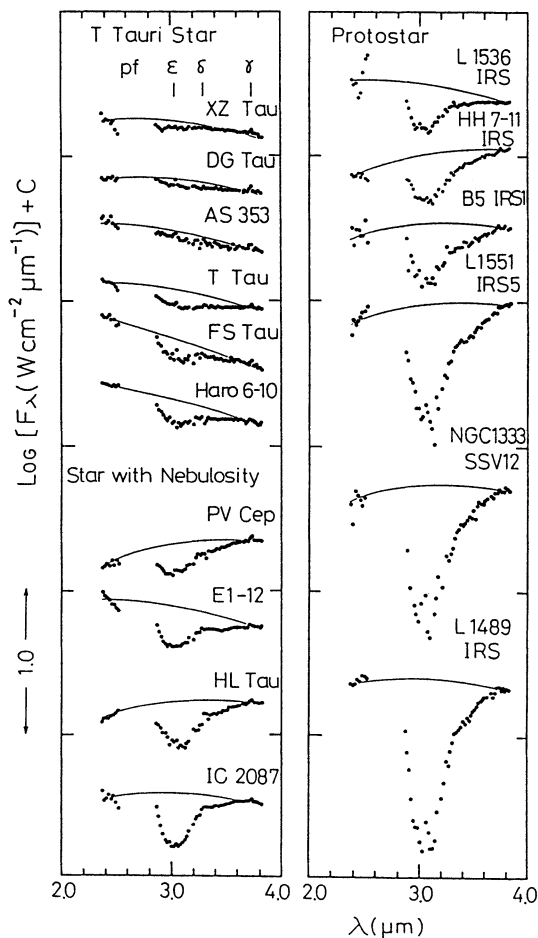


Fig. 2. Spectra of the observed objects grouped into T Tauri stars, stars with nebulosities, and protostars.

protostars to T Tauri stars. The relationship between τ_{ice} and the visual extinction A_v for protostars is in fairly good agreement with that derived from the background field stars toward the Taurus dark cloud, indicating that ice materials, previously frozen onto dust grains as mantles, persist around protostellar envelopes and thereafter most of them disappear at a period in the birth-line.

The apparent color temperatures of the continuum spectra, on which the ice-band is overlaid, are of 800 to 1200 K for protostars, and 1100 to 1500 K for T Tauri stars. After correcting the spectra of the protostars for the foreground extinction (A_v 16 - 30 mag), the color temperatures of the continuum increase to 1200 - 2000 K, roughly in the same range as those of T Tauri stars. This common temperature in both, young T Tauri stars and protostars suggests that the inner boundary of the circumstellar disk is determined by the sublimation of refractory grains. We thus clarified the evolution of ice features; in the earliest phase of star-formation, a central infrared source is enshrouded with a thick and cold cloud, exhibiting the ice absorption band, and thereafter, it will disappear synchronously with their visible appearance out of the disk, that is, transition of the birthline in the H-R diagram.

We extended the program to the other well-known dark cloud near ρ Oph (Tanaka *et al.*, 1990). We obtained the spectra of 31 sources of various kinds in the same wavelength and resolution as for the objects in the Taurus regions. The 3 μm absorption was detected in almost all the embedded sources; protostars, emission line stars, and early type stars. For the seven protostars, which have an H - K magnitude larger than 2 mag, the optical depth at 3 μm due to ice-band absorption, τ_{ice} , increases linearly with H - K in a manner similar to that observed in the Taurus dark cloud, but can be expressed by $\tau_{\text{ice}} = 0.68 (H - K - 1.26)$. This relation indicates the critical visual extinction, $A_{v,c}$, of 10 - 15 mag, larger than 3 mag reported for the Taurus dark cloud (Whittet *et al.*, 1988). The $A_{v,c}$ for the ρ Oph cloud implies the stronger UV radiation fields.

One of the remarkable results is that the emission line stars with the optical depth of 0.2 at 3 μm are present in spite of the fact that their A_v 's are smaller than $A_{v,c}$. This indicates that the ice mantles still remain within their circumstellar disks in an environment with strong UV radiation, if the absorption is assumed to be attributed to H₂O ice.

Following these experiments, Nagata, Kobayashi, and Sato are developing a new version of the Prism Array SpectroPolarimeter (PASP II), which covers wavelengths of 1.4 to 4.2 μm simultaneously with a 32 channel InSb detector array. We aim at making extensive searches for unidentified interstellar bands as well as for the ice band absorption and to investigate the evolution of grain materials and circumstellar disks.

4. Polarization

Polarimetric observations are powerful tools to study (i) distribution and properties of dust grains when polarization arises from circumstellar dust grains and (ii) configuration of magnetic fields when polarization is of interstellar or intracloud origin. Extensive surveys of both, YSOs and background field stars, inside and around certain regions will reveal the geometrical relationship between the circumstellar disks and the surrounding magnetic fields. Polarization surveys of YSOs are, however, rare; Bastien (1982; 1985) conducted a polarization survey for T Tauri stars. He showed that most T Tauri stars are linearly polarized, with generally small and time-variable degrees of polarization, by circumstellar dusts.

Tamura and Sato (1988) carried out polarimetric observation of 39 T Tauri stars in the Taurus-Auriga dark cloud at K-band. Most of the T Tauri stars are linearly polarized, but with relatively small degrees, (up to 3 %), in sharp contrast to the large degrees of polarization (up to 20 %) which have previously been observed in molecular-outflow sources and IRAS low-luminosity sources in the same regions.

On the other hand, polarization survey of background stars lying in the peripheries of the dark cloud have been extensively done in the past decade, which strengthened our belief that magnetic fields play a most dominant role in the entire processes of cloud- to star-formation.

The most remarkable is that the polarizations of YSOs and field stars in a certain area are perpendicular to each other in the number of star forming regions (Tau-Aur dark cloud, L1641, NGC1333, Mon R2, L1551). In addition, the elongation of cloud morphology and the polarization vectors of field stars are perpendicular to each other, indicating that the magnetic fields also control the large-scale morphology of dark clouds (Heiles Cloud 2, L204, NGC1333, ρ Ophiuchi).

Although the previous broad-band polarimetries with a conventional single detector have revealed the geometry of star-forming regions, they provide little information on the behaviors (properties and size-distributions) of dust grains therein. To examine the grain properties, grain size and evolution of circumstellar envelopes, a polarimetric measurement with spectral resolution, even if it is not so high, is of crucial importance, instead of broad band (J, H and K) polarimetry.

With this aim, Takami *et al.* (1990) developed a Prism Array Spectro-Polarimeter (PASP I), which has been successfully commissioned since October, 1989 at the 1.3 m ISAS infrared telescope. Nagata *et al.* remeasured the polarization of YSOs (L1551 IRS5, HL Tau and T Tau) lying in the southernmost area of the Taurus dark cloud with PASP I on the ISAS 1.3 m infrared telescope in January 1990. The parameters were employed as follows; chopping frequency of 2.8 Hz, chopping throw of 30 arcsec. and the field of view of 15 arcsec. We show some preliminary results concerning to the spectropolarimetry in Figs. 3-a, -b, -c (Kobayashi *et al.*, 1991)

Figure 3-a; L1551 IRS5 is well known as an archetype of infrared source with bipolar molecular outflow and dense molecular disk (Snell *et al.*, 1980). Large polarization of up to 28, 24, and 18 % was discovered at the H, K, and L bands, respectively, by Nagata *et al.* (1983), and deep absorption of ice was detected at $3.1 \mu\text{m}$ by Sato *et al.* (1990). Present polarization data are in good agreement with the previous ones, from 1.5 to $2.5 \mu\text{m}$, confirming the cause of polarization to be the scattering by dust grains. The gradual decline of polarization degrees with the wavelength was due to the dilution by the thermal emission from the central source.

Figure 3-b; HL Tau, located $35''$ north-east of L1551 IRS5, shows both, large polarization and ice absorption; polarization in the optical regions are fairly large, of up to 13 % (Bastien, 1982; 1985), while infrared polarizations depend heavily on the wavelengths from 10 % at $1 \mu\text{m}$ to 1 % at $2.2 \mu\text{m}$, confirming the result by Hodapp (1984). It is noteworthy of the dip of a polarization degree and the change of a position angle at $2.3 \mu\text{m}$.

Figure 3-c; T Tau is a prototype of T Tauri stars, but it shows peculiar features among the normal T Tauri stars; large luminosity of $25 L_{\odot}$, association of molecular outflow, Herbig-Haro objects, H_2 molecular emission and water-maser source. The polarization shows interesting behaviors; the degrees are small, of around 1 %, from visual to near infrared regions

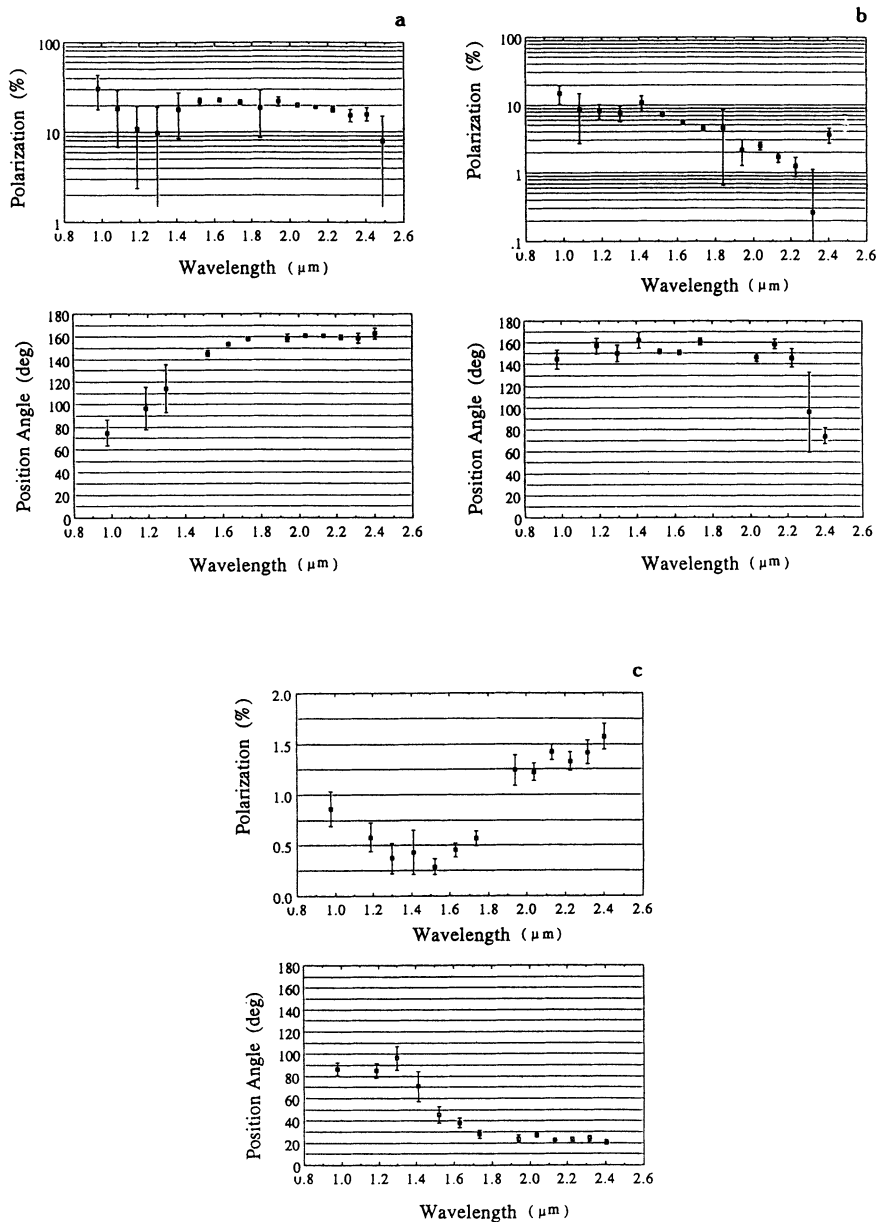


Fig. 3. Preliminary results concerning to the spectropolarimetry of three YSOs (3-a: L1551 IRS5, 3-b: HL Tau and 3-c: T Tau) lying in the southernmost of the Taurus dark cloud.

with a dip at around $1.5 \mu\text{m}$, where the position angles change abruptly from 100 to 10 deg. We interpreted these to be due to the difference of optical thickness of dust envelopes around the central star. T Tau should be surrounded by two kinds of the dust envelopes; a rather thick disk in the equatorial plane and a tenuous and extended envelope off the plane. The visual photons cannot penetrate the disk, but escape in up and down directions of the equatorial plane, where they are scattered and polarized. Near infrared photons can propagate in the direction of the equatorial disk, where it is scattered and polarized by the dust grains therein.

From a viewpoint of polarization, we inferred that the L1551 IRS5, HL Tau, and T Tau form a sequence of the earliest stage of evolution on the H-R diagram, descending from a protostar phase toward a T Tauri star phase. L1551 IRS5 is still embedded deeply within the thick disk, and luminous, 30 L_{\odot} in total, but invisible in the optical wavelengths. T Tau itself, has no or little evidence of ice and polarization, supporting that T Tauri is at a phase of "T Tauri" ages on the way down toward the radiative equilibrium. HL Tau is a key object pivoting the two, just becoming visible on the verge of appearance from the natal cloud and staying around the birth-line on the H-R diagram. The substantial polarization and ice absorption indicate a remnant of the thick disk. A tiny bipolar molecular-outflow was also found in the NE-SW direction, nearly parallel to that of L1551 IRS5 (Sato *et al.*, 1988; Tamura and Sato, 1988).

It is noteworthy that the position angles in infrared wavelengths are aligned with the direction perpendicular to the bipolar outflows, elongations of nebulosities, and interstellar polarization (Hodapp, 1984; Sato *et al.*, 1985).

We have discussed the change of their appearance along an evolutionary sequence in the H-R diagram based on our recent observations of low-resolution spectrophotometries and polarimetries. YSOs shows abrupt changes of the physical properties (optical visibility, spectral energy distribution, ice absorption, polarization, and bipolar outflows) across the "birth-line", which might divide the protostellar and T Tauri stage. The age estimates on the birthline are uncertain and highly speculative, but it should be of 10^4 - 10^5 years. We have reached a superficial understanding of the star formation process for this decade. In the next decade, high resolving powers, in both spectral and spatial domains, will provide the tools to probe

deeply into the star forming regions.

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