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Search for activity signatures in T Tauri stars

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Abstract.

T Tauri stars are young, low mass, pre-main sequence stars. They exhibit a large variety of properties characteristic of earlier as well as later evolutionary phases and represent an important phase in the stellar evolutionary sequence that lies between the low luminosity sources which are deeply embedded in dust and solar type stars. T Tauri stars show uv and IR excesses, and strong and variable emissions in the optical, ultraviolet and x-ray regions.

The exotic behaviour of Classical T Tauri stars are primarily due to the active circumstellar disk and its interaction with the star and the properties of Weak Emission T Tauri stars are mainly attributed to the enhanced stellar activity. I have carried out a systematic study of a group of T Tauri stars using photometric, spectroscopic and polarimetric observations. I will summarize the important signatures of activity in T Tauri stars. I will also present the results of my observations and interpretations based on them.

Keywords : stars:activity – stars:circumstellar disks – stars:pre-main sequence – stars:starspots

1. Introduction

T Tauri stars were identified as a separate class of objects because of their light variability by Alfred Joy (1945). It was largely due to the work of Herbig (1962) they were recognized as pre-main sequence stars. The late type T Tauri stars have masses of about $1M_\odot$ and ages of about a few million years and display a wide variety of phenomena. Bastian et al.

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(1983) defined T Tauri stars as objects associated with star forming regions, exhibiting Balmer lines of Hydrogen and the Ca II H and K lines in emission.

T Tauri stars are broadly classified into Weak Emission T Tauri stars (WTTS) and Classical T Tauri stars (CTTS). The WTTS include mostly weak emission pre-main sequence stars of spectral types later than K0 and Hα emission equivalent width (EEW) < 10Å, while the CTTS are classified as pre-main sequence stars with spectral types later than K0 and Hα EEW > 10Å.

T Tauri stars show drastic light variations on time-scales of hours to months and also uv flaring. Variations on time-scales of 2-10 days are more regular and are apparently due to the rotational modulation of the star with inhomogeneous distribution of cool or hot surface features. Cool spots are usually found in WTTS. The light variations in CTTS are attributed to the presence of hot spots or zones resulting from the impact zones of an accretion flow on the stellar surface from the active accretion disk. The main difference between CTTS and WTTS is believed to be the presence or absence of an accretion disk.

The optical spectrum of a typical T Tauri star consists of a stellar continuum, stellar absorption lines, a superimposed non-photospheric continuum and emission lines. The absorption spectrum is similar to the photospheric spectra of late type dwarfs or subgiants (Appenzellar & Mundt 1989). T Tauri stars show strong Li I 6708Å absorption. The chromospheric non-radiative losses as measured by the Hα emission appear qualitatively similar in WTTS and other late type active stars, but they can be up to 100 times larger in CTTS. The Hα emission in WTTS can be accounted for as entirely of chromospheric origin and accretion disks are currently the standard way to interpret the properties of CTTS. In the modern picture, this emission is associated with the accretion of circumstellar material onto the stellar surface (Muzerolle et al. 1998). Very broad Hα emission can also indicate active accretion.

Choi & Herbst (1996) proposed that the rotation periods of T Tauri stars exhibit a bimodal distribution. Their basic argument is that slow rotators are those which have been prevented from spinning up via magnetic coupling to their circumstellar disks, while rapid rotators are those which have disengaged their disk-lock via disk depletion. So CTTS with active circumstellar disks, in principle, should be slow rotators compared to WTTS. Stassun (2000) carried out extensive photometric study of the rotation among pre-main sequence stars in and around Orion Nebula and detected rotation periods for 254 stars. He found that the distribution of rotation periods is indistinguishable from a uniform distribution. His study also showed that active accretion does not occur preferentially among slow rotators.

2. Activity signatures

The predominant activity indicators in T Tauri stars are the photometric light variations, Hα and other chromospheric line emissions, uv excess and continuum, infrared emissions and excess, polarimetric variability and X-ray emission.

2.1 Light variations

Irregular light variations over time-scales from minutes to decades are characteristics of nearly all members of the T Tauri stars. It is almost certain that several mechanisms contribute to the observed variations in a given T Tauri star. Irregular short time-scale variations of the order of minutes with low amplitudes may be related to flaring phenomenon. Semi-regular/regular, moderate amplitude variation could arise from the rotationally modulated appearance and disappearance of spots and active regions (Herbst 1989). Irregular, large amplitude variations may be caused by a number of sources. CTTS, which have stronger emission lines and infrared excesses as well as a veiled continuum overlying their photospheric spectrum, typically vary in irregular fashion on time-scales of hours to days with amplitudes of a few hundredths to several magnitudes in visual light. The principal source of the modulations is thought to be unsteady accretion. Sudden brightenings which last for a couple of days seem to be a regular feature of CTTS. This phenomenon may be due to very short-lived hot spots produced by the interaction between the accretion disk and the star (Mekkaden 1998).

2.2 Hα emissions

The most classical method of identifying active stars surrounded by disks has been from Hα emission. It is believed that large emission equivalent widths reflect emission arising in magnetospheric columns which transport material from the inner region of a circumstellar disk to the stellar surface. Weaker emission is believed to arise in active stellar chromospheres (Najita et al. 2000). The emission line profiles exhibit large line widths indicative of large-scale gas flows, and often show inverse P Cygni features clearly tracing infall (Edwards et al. 1994). Models with infalling gas via magnetospheric accretion have successfully reproduced these characteristics, such as blueshifted emission peaks, blueward asymmetries as well as total line fluxes (Muzerolle et al. 2002). But the model fails to reproduce the observation, both in total line flux and in shape in DR Tau, one of the most active CTTS. The star exhibits a pure P Cygni profile at Hα that is probably formed almost entirely in the wind; apparently the extremely high mass loss rate provides sufficient optical depth in the wind to produce both absorption and emission in the hydrogen lines.

Studies of line profile variability have shown some evidence of periodicities indicating rotational modulation of accretion flows in a few CTTS (Johns-Krull & Hatzes 1997), although profile variability in many other cases appears to be more stochastic with a variety of time-scales.

2.3 uv excess and continuum

The uv spectrum of the T Tauri star has a weak continuum and several strong emission lines. The continuum is significantly stronger than that observed in main sequence stars of similar spectral type. The uv excess is appreciably larger in CTTS than in WTTS. The most prominent lines in the spectrum are those of Mg II at 2880 Å. Substantial uv emission is thought to arise from material falling in from the disk onto the photosphere. Rebull et al. (2000) did a photometric survey of around 3600 stars in the outer Orion Nebula Cluster and identified disk candidates using the U–V excess. ¿From an optical and NIR photometric study of the young open cluster NGC 2264 (age 3 Myr and distance 760 pc), Rebull et al. (2002) used U–V excess to detect circumstellar candidates. Since uv excess is expected to probe the same physical process as Hα, there exists a good correlation between these two indicators.

2.4 Infrared emission and excess

CTTS show large IR excesses and they can be identified from near-infrared excesses, thought to be produced from thermal heating and accretion activity in the inner circumstellar disk. Rebull et al. (2002) used I–K and H–K excesses to pick out disk candidates in NGC 2264. They tried to relate the excess indicators to Hα since the latter is supposed to arise in accretion columns and NIR excesses are thought to originate in the disk itself.

2.5 Polarimetric variability

Polarization variations have been observed in several T Tauri stars. The general properties of polarization in T Tauri stars were first surveyed by Bastian (1985). There exists no standard polarization relationship between the linear polarization (P%) and wavelength (λ). Bastian concluded that the observed polarization is due to scattering by dust grains of stellar radiation and their extended emission regions. Usually in T Tauri stars two types of polarization variability are observed, polarization outbursts and small amplitude variations. The small amplitude variability may be due the presence of inhomogeneities in the circumstellar environment or due to spots on the stellar surface. Periodic polarimetric variability has been detected only in very few systems (Mekkaden 1999). Simulations of photopolarimetric variability of spotted star plus disk have been carried out by Wood et al. (1996) where predictions were made for *V* band. The modeling by Stassun (2000) confirms that the accretion model is consistent with existing observations of photopolarimetric variability.

3. Observations and Results

In order to study the peculiar properties of T Tauri stars, it is necessary to carry out observations at all possible wavelengths using various techniques. A group of T Tauri stars were investigated using photometric, spectroscopic and polarimetric observations and these were made simultaneously whenever possible. The group includes the CTTS TW Hya and V4046 Sgr and the WTTS V410 Tau.

3.1 TW Hya

TW Hya is a peculiar T Tauri star. It shows light variations in V between 10.9 to 11.3 mag and the Hα EEW variation between 70 to 250 Å. The star also shows short time-scale variations. Rucinski & Krautter (1983) classified TW Hya as a member of CTTS on the basis of its strong Hα and other emission lines, uv and IR excess, Lithium abundance and irregular light variations.

Photometric observations of TW Hya were carried out during 34 nights over 4 seasons (1987, 1988, 1990 and 1993) and near-simultaneous spectroscopic and polarimetric observations were done during one season (1993). Analysis of the photometry showed that the star exhibits periodic light variations during some epochs with a period of 2.196 days. The sharp increase in the amplitudes of light curves towards shorter wavelengths is attributed to the presence of highly active hot spots on the stellar surface. Modeling of light curves indicate the presence of a polar hot spot that covers a very small fractional surface area, probably caused by the channeled magnetospheric accretion from the circumstellar disk. The Hα EEW shows sudden changes and varies between 190 to 250 Å. Fig.1 is the plots of linear polarization (P%) and position angle (θ°) in V phased with the rotation period. The polarization measurements show the presence of two components; a periodic low amplitude modulation of polarization and sudden increase in polarization that lasts for a few days, probably caused by short-lived hot spots. The observations strongly suggest the existence of an active circumstellar disk accreting on to the star. A detailed discussion of observation and analysis of TW Hya is given in Mekkaden (1998).

Muzerolle et al. (2000) used radiation transfer models of magnetospheric accretion to explain Hα emission in TW Hya. The model reproduces the observed flux at Hα and the accretion shock has a filling factor f=0.3% of the stellar surface. The small value of filling factor is consistent with the hot spot models of photometric variability postulated in our study. Recently, Trilling et al. (2001) have done ground-based near-infrared imaging of the circumstellar disk around TW Hya. They detected a face-on disk with a radius of 4 arcseconds.

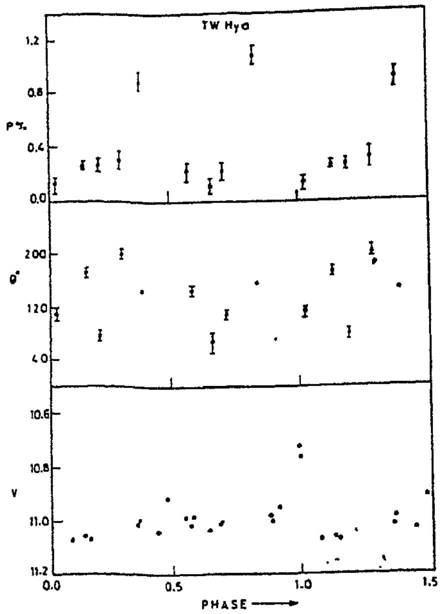

Figure 1. Plots of linear polarization and position angle in V of TW Hya phased with period. The lower panel is the overlapping photometry

3.2 V4046 Sgr

Busko & Torres (1976) detected the light variability of V4046 Sgr. Byrone (1985) discovered the double-lined spectroscopic nature of the star. His radial velocity measurements gave an orbital period of 2.45 days and also found that the Hα emission strength, which varied between 30 and 100 Å, showed modulation with a period similar to the orbital period. From a detailed study, de la Reza et al. (1986) classified V4046 Sgr as a member of CTTS. The strong and variable Hα emission and excess emissions in infrared and far-infrared wavelengths indicate the presence of material having wide range of temperatures and extending over large distances from the component stars.

Photometric observations of V4046 Sgr were carried out on a total of 40 nights over 4 seasons (May 1988, June 1988, 1989 and 1990) to search for periodic light variations and sudden brightenings that are usually observed in CTTS. The secondary component is fainter than the primary by 0.7 mag; so the light contribution to the total light variation by the secondary is not significant. The extensive photometric data obtained during August 1990 was analyzed using a period finding technique resulting in a period of 2.445 days. Figure 2 is a plot of the observations phased with the derived period. The minimum scatter in the light curve indicates that the surface brightness inhomogeneity on the primary that caused the light variation remained in the same location and also without any appreciable change throughout the observing run of around 5 rotation periods.

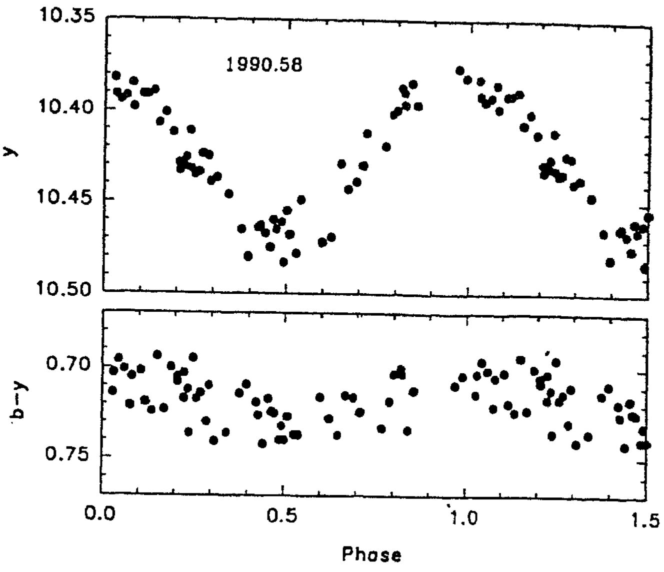

Figure 2. Plots of y and b–y of V4046Sgr

The shape and the minimum scatter in the light curve could be an indication that the inhomogeneity was caused by cool spots. But at some other epochs the light curves of V4046 Sgr show larger scatter and also sudden changes in shape as is usually seen in stars with hot spots. Vrba et al. (1993) have shown that both the periodic and irregular light variations of the CTTS can be explained in terms of a changing mix of cool and hot spots on their surfaces. This may be the case in V4046 Sgr.

Spectroscopic observations at Hα have revealed that the EEW vary from 39 to 80 Å. But the observations do not have enough phase coverage to check any periodic variation in Hα emission strength. The strong emission is an indication of accretion from the circumstellar (or circumbinary) disk. Linear polarization observations show that the star exhibit variable polarization. Sudden variations in P% and θ°were observed within a few days. It is possible that the geometry of the circumstellar material as well as the illuminating source changes in V4046 Sgr. The interpretations of observations are given in Mekkaden (2000).

3.3 V410 Tau

V410 Tau is one of the most investigated T Tauri star. It has weak Hα emission and little infrared excess (Rydgren et al. 1984, Rucinski 1985). So V410 Tau is a typical weak emission T Tauri star. From an extensive photometric study, Petrov et al. (1994)

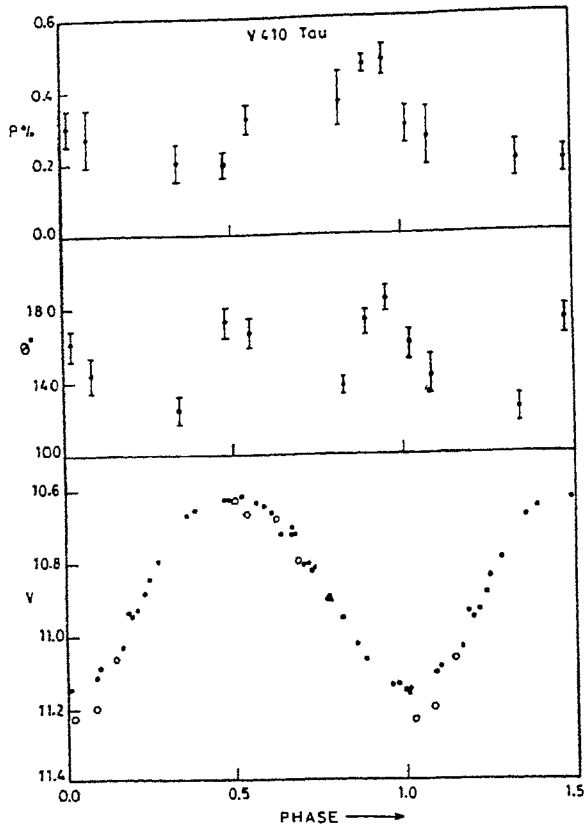

Figure 3. Plots of V band linear polarization and position angle of V410 Tau phased with the period. The lower panel is the overlapping photometry

refined the photometric period as 1.872 days. The shape and amplitude of the light curve remains more or less the same over several hundred rotation periods, implying the long-lived nature of the spot group that causes the light variation.

Polarimetric and spectroscopic observations of V410 Tau were carried out in 1993 to study the nature of the polarization variability and Hα emission variations. Simultaneous photometric observations were also done and it was found that these observations match with that made by Petrov et al. (1994) six months earlier. Figure 3 is a plot of V band linear polarization (P%) and position angle (θ°) phased with the period. The lower panel shows the simultaneous photometry. The filled circles are the observations of Petrov et al. (1994) and the open circles ours. The P% shows a periodic variation that is in anti-correlation with the light variation. The position angle θ°also shows a periodic trend. Modeling of the light curve indicates that two adjacent cool spot groups could cause the observed variability. The observed periodic variability in linear polarization may be due to these spots causing variable illumination of the circumstellar dust envelope as the star rotates.

The Hα line exhibits variation from a shallow absorption to moderate emission. The maximum Hα emission occurs when the star is at its minimum light and vice versa. This indicates that the chromospheric active regions that produce Hα emission and the photospheric cool spots are nearly co-spatial (Welty & Ramsey 1995). The observation and the interpretation mentioned here are given in detail in Mekkaden (1999).

4. Conclusions

T Tauri stars are very complex systems and their properties mainly depend on the initial conditions of star formation. The peculiarities shown by CTTS are due to the presence of active circumstellar disks. The magnetically channeled accretion from the disk to the star produces hot spots and the strong emissions observed at several wavelengths. In the case of WTTS most of the activity can be explained in terms of enhanced stellar activity. They usually do not show any evidence of active circumstellar disks; probably the disks have already dissipated. It is of significance to note that the CTTS TW Hya, which is 10 Myr old, has an active circumstellar disk. The disk dissipation times vary from star to star and may depend on the initial conditions of their formation.

For a proper understanding of the activity in T Tauri stars, a sustained long-term observations at all possible wavelengths are required. The rotation periods and sudden flaring can be detected by carrying out photometry, and especially infrared photometry helps to identify stars with circumstellar disks. Modeling of Hα emission lines of CTTS leads to the determination of accretion rates from circumstellar disks. The disks can also be imaged at infrared wavelengths using coronagraphic techniques.

Young clusters like the Orion Nebula Cluster and NGC 2264 are the ideal systems to study the characteristics of T Tauri stars. Carpenter, Hillenbrand & Skrutskie (2001) carried out extensive J, H, K time-series photometry over a region centered near the trapezium region of Orion Nebula Cluster using the southern 2MASS telescope. They have identified 1235 near-infrared variable stars. Their analysis show that some variables have NIR colors characteristic of young low mass CTTS surrounded by optically thick accretion disks. Though a large amount of data and analyses on T Tauri stars are currently available further multi-wavelength investigations are necessary to evaluate the life-times of circumstellar disks and also the formation of planetary bodies.

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