Young Stars Near Earth: Progress and Prospects
ASP Conference Series, Vol. 244, 2001
Ray Jayawardhana and Thomas Greene, eds.

Can Post T Tauri Stars Be Found? Yes!

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Abstract. I review the observational challenges of finding post T Tauri stars (PTTS), defined here as low-mass, pre–main-sequence stars with ages of 10^7–10^8 yr. Such stars are difficult to find because they are less active than younger T Tauri stars, and they may not be associated with molecular gas. They are useful for studying the evolution of circumstellar disks and stellar activity between the 10^6-yr ages of nearby star-forming regions and the main sequence. However, care must be taken in the search process so that the selection criteria used to locate such stars do not bias the sample used for subsequent evolutionary studies.

1. Introduction

In an influential 1978 paper, Herbig raised the question "Can Post T Tauri Stars Be Found?" (Herbig 1978). More than twenty years later, armed with the benefit of hindsight and data from astrometric space missions and all-sky surveys at various wavelengths, we can clearly answer "yes" to this question. However, the problem of finding such stars, particularly away from clusters, is still an interesting and challenging one. In this contribution, I discuss the difficulties inherent in trying to identify pre–main-sequence stars that are somewhat older than those found in regions of active star formation and are located in the field.

2. What is a Post T Tauri Star?

Herbig (1978) noted that T Tauri stars have "several distinct observational characteristics," namely strong Hα emission, high surface lithium abundance, irregular variability, and excess infrared emission, and he noted that these are "diminished or absent" in low-mass main-sequence stars. Thus, he defined PTTS as those stars that display intermediate values of these characteristics.

The difficulty with adopting such a definition is that it begs the question of how these properties evolve with time during the pre–main-sequence evolution of a star. By *assuming* evolution as part of our definition, we are defining away our ability to study those stars in which the evolution of one or more of the properties listed above may be particularly fast or slow. As a case in point, it was not until the availability of abundant x-ray data from the Einstein satellite in the 1980s that we realized that infrared excess and strong Hα emission are not ubiquitous features of T Tauri stars (e.g., Walter 1986). It took an observational advance (in this case the launch of x-ray satellites) to allow the detection of young stars based on a characteristic that was not part of the original definition of the group, thus allowing the study of the full range of infrared excesses exhibited by the T Tauri population.

Thus, here I adopt an age-based definition of post-T-Tauri stars (PTTS). For the purpose of this review, I consider a PTTS to be a low-mass pre–main-sequence star with an age of 10^7–10^8 yr. The lower bound corresponds roughly to the oldest stars found in nearby active star-forming regions such as Taurus-Auriga and Ophiuchus, while the upper bound is roughly the age at which solar-mass stars reach the zero-age main sequence or ZAMS (e.g., Siess, Dufour, & Forestini 2000). If we use age as the defining characteristic of a PTTS, then we are free to study the full range of stellar and disk properties exhibited by such stars, and to explore the evolution of these properties with stellar age.

The downside of using an age-based definition is that determining the age of a star that is not in a cluster typically requires knowledge of its distance in order to place it on a theoretical HR diagram for comparison with evolutionary tracks. However, the topic of this meeting is young stars *near* Earth; we are fortunate to live at a time when many of the nearby stars have well-determined distances from Hipparcos, and many more will soon have accurate distances from FAME (Greene, this volume) and GAIA. Thus, our prospects for determining the ages of a statistically significant sample of nearby young stars are better than ever.

Unfortunately, the age of a star is not unambiguously determined by its position in the HR diagram. Stars may appear to lie above the ZAMS for reasons that are both astrophysical and observational in nature. Most obviously, both pre–main-sequence and post–main-sequence stars occupy this region of the HR diagram. In addition, observational uncertainties (including distance and temperature errors, and the presence of unresolved binary companions) can cause a main-sequence star to appear to lie above the ZAMS. Finally, even the comparison of error-free observations with theoretical tracks is not without difficulties. Different sets of tracks place the ZAMS at somewhat different positions in the HR diagram (see, e.g., Stauffer, this volume), and transformation between the observed quantities of apparent magnitude and spectral type (or color) and the L and $T_{\rm eff}$ of the theoretical HR diagram can introduce uncertainties as well.

3. Characteristics of PTTS

Clearly, then, even when defining PTTS by age we need to understand the unique observable characteristics of such stars in order to be able to determine stellar ages and thus classify individual stars unambiguously as PTTS. In this section, I consider some observable properties of PTTS that may help us distinguish them from older stars.

At first glance, this appears to be almost exactly what I claimed above we do *not* want to do: define a group of stars based on one or more secondary characteristics, since this impairs our ability to study the evolution of that characteristic. However, I am not abandoning an age-based definition; I am simply suggesting that, even when using age as our defining characteristic, we must rely somewhat on secondary characteristics to establish a young age observationally. I will argue below that such an approach can still allow us to study stellar and disk evolution if we are careful about choosing which secondary characteristics to consider and if we are aware of how these characteristics are interrelated.

Therefore, I now briefly review some distinguishing properties of young stars, with a particular eye toward how such properties can help us distinguish young from old stars, and how some of these properties are interrelated. Each of these properties has been the subject of numerous reviews in the literature. The aim here is not to cover each property exhaustively, but merely to provide an overview of how it fits into the study of PTTS. Variability and kinematics are also useful indicators of youth, but they are not discussed below for reasons of limited space.

Lest it get lost in the details that follow, I stress the following basic point. Position in the HR diagram is most useful for distinguishing between pre–main-sequence and ZAMS stars; secondary indicators are less useful for this. On the other hand, secondary indicators such as lithium and x-ray emission are most useful for distinguishing between pre– and post–main-sequence stars; position in the HR diagram is less useful for this. Thus, the combination of HR diagram position and one or more of the following secondary indicators of youth yields the most effective strategy for finding PTTS.

3.1. Infrared excess

At ages of 10^6 yr, more than 50% of low-mass stars show excess infrared emission above their photospheric emission (Meyer & Beckwith 2000; Haisch, Lada, & Lada 2001). This emission arises in circumstellar disks. At PTTS ages, the fraction of stars retaining substantial disks is very uncertain; this question is the subject of active study (e.g., Spangler et al. 2001; Meyer & Beckwith 2000). Certainly some PTTS still show evidence for disks, with two notable examples being TW Hya (Rucinski & Krautter 1983) and HD 98800 (Zuckerman & Becklin 1993). At the $\sim 10^8$ yr age of the Pleiades, very few stars have detectable infrared excess (Meyer & Beckwith 2001). While a small fraction ($< 1\%$) of giants have infrared excesses (de la Reza, Drake, & da Silva, 1996), these stars are rare, so the presence of a strong infrared excess is in general an indicator of youth.

3.2. Hα emission

Strong Hα emission is another defining characteristic of the youngest stars. T Tauri stars show a range of emission-line strengths, with Hα emission equivalent widths ranging from a few Ångstroms up to several hundred Ångstroms. The stars with the strongest Hα emission lines (EW $\gtrsim$ 10 Å) almost invariably show infrared excesses as well, and it is believed that the emission arises from the heating of disk material as it is accreted onto the star. Weaker emission lines (or filled-in absorption lines) can arise from chromospheric activity. Strong Hα emission is clearly tied with the presence of disks in PTTS as well; it was the strong Hα emission of TW Hya in the objective prism survey of Henize (1976), coupled with its high galactic latitude, that first brought it to the attention of Herbig, causing him to label TW Hya as a candidate PTTS (Herbig, personal communication).

3.3. X-ray emission

Young stars as a group have a higher mean x-ray luminosity than older stars; comparison of clusters of different ages shows that the median x-ray luminosity declines steadily with age from 10^6 yr to at least 10^8 yr (Briceño et al. 1997). The distance-independent ratio L_X/L_{bol} also declines with age.

The spread of x-ray luminosities at a given age is such that it is difficult to distinguish ZAMS stars from pre–main-sequence stars on the basis of x-ray luminosity or L_X/L_{bol} alone (Briceño et al. 1997). However, giants with strong x-ray emission are very rare, so a high L_X/L_{bol} ratio is a useful discriminant between pre– and post–main-sequence stars. The exception to this is that short-period binaries maintain high levels of activity throughout their lives due to the tidal locking of the stellar rotation periods with the binary orbital period.

3.4. Lithium abundance

Lithium is a tracer of stellar youth since it is destroyed at temperatures of around 10^6 K, and late-type stars have outer convection zones that carry surface material down to layers of the star with these temperatures. As convection carries the lithium-depleted material back to the surface, the photospheric lithium abundance in these stars steadily declines with age. Thus, the presence of a strong lithium line in the spectrum of a star with a spectral type of roughly G5 or later is a good indicator of youth.

However, there are a few caveats to this statement. First, stars with spectral types earlier than about G0 do not have deep enough convection zones to deplete lithium significantly, and G0–G5 stars deplete lithium very slowly. Also, at a given age, there is a range of observed lithium equivalent widths at any given spectral type (e.g., Soderblom et al. 1993). This seems to be tied to rotation rate, with rapidly rotating stars depleting lithium less quickly. Jeffries (1999) has suggested that in fact there may be no spread in lithium *abundance* at a given spectral type and age, and that the observed Li equivalent width spread is instead accounted for by a spread in the fraction of a star covered by spots. There is also a small population of lithium-rich giant stars; these comprise $\lesssim 1\%$ of giants (Brown et al. 1989). There is some question in the literature about whether or not the Li-rich giants tend to be rapid rotators (De Medeiros et al. 2000; Charbonnel & Balachandran 2000). Some of the Li-rich giants are also those that show infrared excesses (de la Reza et al. 1996).

4. PTTS Search Strategies

Given these properties, how then should one search for PTTS? There is no single answer to this question. Given the rich set of PTTS properties discussed above, clearly there are many ways that one could proceed, with the optimum search strategy depending on the astrophysical questions that one wishes to use these stars to study.

The conclusions of Wichmann (2000) are of great relevance for any survey for isolated PTTS. He points out that any survey for objects that are intrinsically rare (including PTTS, since the pre–main-sequence phase is a small fraction of a star's life) is much more likely to yield false positives (old stars misidentified as young) than it is to yield false negatives (young stars misidentified as old). However, he also notes that the frequency of false PTTS positives declines dramatically when selection based on both lithium and x-ray emission is used. More generally, that is one of the fundamental points of this paper. Given the complicated nature of the PTTS and the degeneracy of many of the secondary selection criteria, use of multiple criteria is not only useful, it is nearly essential in building a convincing case that a star is a PTTS.

4.1. Studies of disk evolution

One of the exciting uses of a sample of nearby PTTS would be to allow detailed study of disk properties in the planet-building phase at ages of 10^7–10^8 yr. Some early surveys for PTTS, such as the Pico dos Dias survey (de la Reza et al. 1989; Gregorio-Hetem et al. 1992; Torres et al. 1995), used IRAS fluxes as a selection criterion. Thus, these surveys are biased toward stars (such as TW Hya) with long-lived disks. In order to study the evolution of disks, we must select stars in a way that is unbiased with respect to disks. From the criteria above, perhaps the best candidates are x-ray emission and Li abundance, neither of which should be greatly influenced by the presence of disks.

In an attempt to establish a "clean" sample of PTTS for studying disk evolution, I have begun a survey of stars selected for high x-ray activity and position above the main sequence using the ROSAT Bright Source Catalog and the Hipparcos Catalog (Jensen et al., in preparation). This approach is limited by the magnitude limit of Hipparcos, but it holds great promise for use with FAME. This x-ray and optical selection recovers a number of known PTTS (including members of the TW Hya and Tucana associations), suggesting that it is effective for finding PTTS. Follow-up spectroscopy of stars not already known to be young has revealed a handful of stars with strong Li absorption and Hα emission. Preliminary analysis suggests that most of these are loosely associated with the large Sco-Cen-Lupus molecular cloud complex or the Carina-Vela moving group (Makarov & Urban 2000).

4.2. Studies of multiplicity or stellar rotation

In contrast to studying disk evolution, studying the evolution of multiplicity (at least at the shortest periods) or stellar rotation with a sample of field PTTS is problematic. Stellar rotation is tied to multiplicity in the sense that short-period spectroscopic binaries become tidally locked, causing the stars to rotate with the binary orbital period. This high rotation rate in turn leads to stronger-than-average chromospheric and coronal activity (yielding a high x-ray luminosity) and may delay the depletion of lithium. Thus, any sample that is selected based on lithium and/or x-ray criteria may be biased toward having a high fraction of spectroscopic binaries and rapidly-rotating single stars. On the other hand, these concerns may not apply to multiplicity at wider separations, unless the presence of a short-period companion reduces the likelihood that a star also has a wider companion.

5. Conclusions

The essential point of this contribution is that post T Tauri stars *can* be found, but that their properties are complex and interrelated. Few if any of these properties uniquely determine the age of a star, so secure classification of any field star as post T Tauri must rest on the use of multiple criteria, most powerfully a combination of position in the HR diagram and one or more of the secondary criteria discussed above. In choosing which criteria to use in PTTS searches, we must carefully consider how these criteria relate to (and possibly bias) the astrophysical properties we wish to study using the PTTS.

Acknowledgments. I thank George Herbig for inspiring me to enter this field of study with his 1978 paper, and I apologize for borrowing that paper's title and pressing it into service for my own purposes. I also thank him for answering my questions about his early studies of TW Hya. I thank Keivan Stassun, Rabi Whitaker, and David Cohen for useful conversations.

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