NON COEVAL YOUNG MULTIPLE SYSTEMS?

On the pairing of protostars and T Tauri stars

Gaspard Duchêne, Andrea Ghez & Caer McCabe
UCLA – Department of Physics & Astronomy
Los Angeles, CA 90095-1562, USA
duchene@astro.ucla.edu, ghez@astro.ucla.edu, mccabe@astro.ucla.edu

Abstract
We summarize here the observed properties of “infrared companions” to T Tauri stars and argue that their observational properties are identical to those of Class I sources. They may therefore be embedded protostars in a much earlier evolutionary phase than T Tauri stars, in which case these multiple systems are significantly non-coeval as opposed to the majority of young binary systems. They would have formed through a different mechanism than core fragmentation. The only distinction between IRCs and Class I sources is that they lie within a few tens of AU of a T Tauri star, and so they cannot be at the center of a vast optically thick envelope as is believed to be the case for protostars. We discuss whether systems with an IRC are really candidates for non-coeval multiple systems.

1. Introduction

Binary and higher order multiple systems are the most frequent outcome of the star formation process and, as such, they represent a direct probe of this process. In the most widely accepted model to date, giant molecular clouds first give rise to a number of individual clumps, or cores, that subsequently undergo a collapse to finally form a central star. During this collapse, fragmentation may occur, due to rotation, turbulence or ambipolar diffusion of the magnetic field for instance, that leads to the formation of ~2–5 physically associated objects which eventually evolve into a stable multiple system. One of the basic predictions of this scenario is that binary systems should be tightly coeval, to within a free-fall time of the original core (~10^6 yrs). Observational campaigns to test this prediction on large populations of T Tauri binary systems have been conducted for several years (e.g., Hartigan et al. 1994; White & Ghez 2001) and have concluded that binary systems are remarkably co-
eval, at least to within $< 10^6$ years. Therefore, observations tend to favor core fragmentation as the dominant process of forming binary stars.

Among all T Tauri binary systems, there is a small category of remarkable objects named “infrared companions” (IRCs). These are defined as companions to known T Tauri stars that can only be detected in the infrared (IR) and that display “extremely” red IR colors, probably because of a large line-of-sight extinction. The most prominent IRC is the companion to the prototypical object T Tau (Dyck et al. 1982). The status of this class of objects was first discussed by Zinnecker & Wilking (1992) and a good compilation of observations can be found in Koresko et al. (1997), after which a few more IRCs were identified. As we will discuss here, these systems are problematic, as they seem to pair a normal T Tauri star with a much more embedded, and qualitatively much younger, protostar. They would therefore be non-coeval systems, contrasting with most young binary systems.

Since the review by Koresko et al., additional high spatial resolution data have been obtained and information about the dynamics of the systems have been gathered by us and others. Here, we summarize those results and discuss how they fit into the binary coevality issue.

2. Observational properties of IRCs

2.1 A naive look at IRCs: an age paradox

In the well-studied Taurus-Auriga star-forming region, 5 IRCs are known among a sample of $\sim 120$ stars, representing a mere 4% of the overall population. The masses and ages of their optically bright primaries are in the ranges $\sim 0.2 - 2 M_\odot$ and $\sim 0.1 - 5$ Myrs respectively. The projected separations range from $\sim 10$ to a few hundred AUs, similar to the range of separations for normal T Tauri binaries. Also, most systems show thermal millimeter emission associated with cold circumstellar material although in general it is not known with which component it is associated. The fact that some of these IRCs have (at times) been detected in the visible raises the possibility that intrinsically different objects are erroneously assembled in the same category.

As a first step to determining the nature of IRCs, Koresko et al. (1997) compiled the spectral energy distribution (SED) for each IRC from the visible up to $100 \mu m$. They all showed a similar shape, with a very broad peak centered between 5 and 20 $\mu m$ depending on the object. The corresponding bolometric temperatures are much cooler than any stellar photosphere, only a few hundred degrees. Assuming that they radiate isotropically, the bolometric luminosities of IRCs range from $\sim 0.8$ to $12 L_\odot$. Taking these values at face value and plotting them against
other young stellar objects as well as against the protostar evolution models of Myers et al. (1998), one finds that IRCs fall in the same part of the diagram as Class I sources, protostars embedded in a moderately massive, contracting circumstellar envelope. Therefore, if one were to classify IRCs on the basis of their SED only, one would undoubtedly conclude that IRCs are Class I protostars.

T Tauri stars in general, and those that have an IRC in particular, have typical ages of 1–5 Myr. On the other hand, it is generally admitted that the small numbers of Class I protostars implies that they are much younger, typically a few $10^5$ yrs. It therefore appears that IRC systems are non-coeval, with multi-Myr age differences. Three general explanations can be proposed to account for these systems: i) some multiple systems are really non-coeval, in which case one must explain how they formed; ii) IRCs only look like protostars but are in fact T Tauri stars disguised as protostars; and iii) the T Tauri stars associated to IRCs are in fact much younger than we think they are and these systems are in fact extremely young, coeval systems.

2.2 A purely geometrical explanation?

Among the three explanations suggested above, the idea that IRCs are in fact normal T Tauri stars in a peculiar geometric configuration is the most widely believed (e.g., Koresko et al. 1997). Such objects would look like protostars if they were heavily extincted by some circumstellar material, as none or very little flux shortward of 1 $\mu$m would reach the observer while at long wavelengths one would detect the thermal emission of the dusty material that enshrouds the central star.

There are two types of configurations that would lead to the observed SEDs for IRCs. The first one is the case of a star that is embedded in an optically thick dusty envelope so that the only light we receive from the star has been reprocessed. Alternatively, IRCs could be T Tauri stars surrounded by an unresolved optically thick circumstellar disk that is seen at an almost edge-on inclination. Both observations and radiative transfer models of such objects show that their SED is extremely suppressed shortward of $\sim 10 \mu$m, resulting in a predominant mid-IR peak, similar to those of Class I sources (D'Alessio et al. 1999; Wood et al. 2002). In this case, the inferred bolometric luminosity assuming isotropic radiation can be 1–2 orders of magnitudes lower than its actual value because the visible/near-IR light is predominantly scattered away from the observer's line of sight.

A relatively straightforward observational test can discriminate the two scenarios presented here: if the star is embedded into an optically
thick envelope, its near-IR (and visible if observed) spectrum is featureless as it has been reprocessed by warm dust. On the other hand, in the edge-on disk scenario, the received spectrum has only been scattered at the surface of the disk and has retained the intrinsic photospheric features of the central object. This has for example been verified for the edge-on disk source IRAS 04158+2805 (Ménard et al. 2003).

3. Recent observations of IRCs

Over the last few years, at least two new IRCs have been identified, WL 20 S and V 773 Tau D (Ressler & Barsony 2001, Duchêne et al. 2003), and several high angular resolution datasets have been obtained, both in imaging and spectroscopic modes, for several systems, allowing a more complete understanding of their properties.

First of all, IRCs are extremely variable, by up to several magnitudes even in the mid-IR. This was already known for some of them (e.g., T Tau: Ghez et al. 1991) and has also been observed for V 773 Tau D (Duchêne et al. 2003). Also strong absorption features of both water ice and silicates have been observed in the IR (Hanner et al. 1998, Beck et al. 2001). These features unambiguously show that IRCs are observed through large column densities of dusty material. The photometric variability is however unlikely to be fully explained by a varying line-of-sight extinction: variations in the emission of the central source has to be present as well (Beck et al. 2001; Leinert et al. 2001).

Recent near-IR spectroscopy of several IRCs (Haro 6-10 N, T Tau S, V 773 Tau D) have revealed featureless spectra, with the exception of atomic and molecular hydrogen in emission (Herbst et al. 1995; Beck et al. 2001; Duchêne et al. 2002, 2003). This excludes the possibility of these IRCs being K- or M-type T Tauri stars extincted by an edge-on circumstellar disk. Note that this result is not inconsistent with IRCs being earlier spectral type (i.e., higher mass) objects seen behind an edge-on disk. This is discussed in more details in the following section.

The case of T Tau S is quite revealing since this IRC is located in a triple system (Koresko 2000). Most importantly, Duchêne et al. (2002) have shown that the tight companion to the IRC, which is located only 10–12 AU away, is a normal, though heavily extincted, T Tauri star with an M0.5 spectral type. This implies that what makes an IRC so special is confined within a few AU of the central object. If it is an opaque circumstellar envelope, it has to be quite dense in order to be optically thick despite such a small radius.

Finally, the most exciting new result regarding IRCs concerns their dynamical status. Most of them are located at a few hundred AU and the
orbital periods for those systems are on order of a thousand years. However, T Tau S is in a 10 AU-binary and we can expect its orbital period to be about 15–30 yrs. Since its first discovery in 1997, several measurements of the binary separation have been made and clear evidence of orbital motion has been found (see Fig. 1). In November 2000, the relative velocity of the binary in the plane of the sky was on order of 13±4 km/s (based on a quadratic fit). Furthermore, we have also obtained spatially resolved high spectral resolution near-IR spectra of both components of the system. We found a relative velocity of 20±2 km/s. This combines to a three dimension relative velocity of about 24±4 km/s which implies a minimum system mass of $M_{TTauS} \geq (4.2 \pm 1.5)(\frac{D}{140 \text{pc}})^3 M_\odot$, if the system is physically bound. This is much more than the estimated mass of T Tau Sb and T Tau N, suggesting that the IRC is the most massive object in the T Tau multiple system. So far, the measurements do not cover enough of the orbit to allow a complete orbital solution fit but this should be feasible in just a few years.

A controversial result concerning this system was recently obtained by Loinard et al. (2003) using archival VLA centimeter data. At these wavelengths, only T Tau N (the well known T Tauri star) and T Tau Sb (the extincted close companion to the IRC) are detected. Still, they concluded that the T Tau Sa–Sb system is unstable and that T Tau Sb has been ejected in the last few years on a higher (possibly open) orbit. This is reminiscent of the “disrupting triple systems” proposed by Reipurth (2000), which were candidates for forming IRC systems. In this scenario, a very young (a few $10^5$ yrs-old) triple system undergoes an unstable triple encounter and one of them is ejected in one direction while the remaining binary experiences a slow recoil motion in the other direction. The single star would then escape the opaque envelope still surrounding the system and therefore become optically visible while the other two components would remain heavily obscured (this is the third scenario mentionned in § 2.1). However, this scenario is not very well supported by our IR images, which show a clear slowdown of the motion
of T Tau Sb between 2000 and 2002, suggesting that its orbit is bound. Only future observations will tell what type of orbit this star is on.

In the case of V 773 Tau, the IRC has not been monitored long enough to allow a proper orbital fit. However, all observations are consistent with the system being hierarchical, as well as possibly coplanar, and therefore dynamically stable. Most other IRCs are located in binary systems and, unless a third component is later discovered, they are necessarily in two-body stable systems. Until further measurements prove otherwise, we conclude that IRCs are in stable systems and that Reipurth’s scenario is not generally the cause for these unusual IRCs.

4. The high-mass star hypothesis

One of the scenarios presented above to account for the observed properties of IRCs is that they are high- to intermediate-mass stars obscured by a circumstellar disk seen edge-on. This is a likely situation in Glass I, since its spectral type has been estimated to be G5 (Feigelson & Kriss 1989) but is clearly inconsistent with the spectral type of UY Aur B (M2, Duchêne et al. 1999). In systems with featureless IR spectra, the central star could be an A- or F- type star, preventing any line detection if the star is accreting material (accretion produces hydrogen line emission that fills photospheric features). Also, such objects would have large luminosities, \( \gg 10 L_\odot \), but only a fraction of it would be seen by the observer because of the peculiar geometry. This would explain the observed luminosities of IRCs. Finally, in the case of T Tau S, a relatively large mass is required for the IRC if the system is physically bound. The high-mass star hypothesis is therefore a significant possibility that needs to be studied in more details.

One way to test this hypothesis is to obtain high-resolution spectra of IRCs and try to find some photospheric features in them. It is for instance suggestive that, in our radial velocity measurement, we obtained the strongest cross-correlation peak for T Tau Sa with the spectrum of an F8 template star (we used M5 to F8 templates). A larger set of templates is however required to determine accurately the actual intrinsic spectral type of this IRC. Another possible test consists in analyzing the spectrum of the scattered light nebula surrounding T Tau. If the IRC is a 3–5 \( M_\odot \) star, it is by far the most luminous object in the system and it should be the dominant source of illumination for the nebula.

5. Are IRCs bona fide protostars?

If IRCs are not high-mass objects, then they have to be surrounded by compact optically thick circumstellar envelopes. It is then natural
Non coeval young multiple systems?

that they have similar properties as Class I protostars, as they are virtually identical: a central point source surrounded by a lighter but opaque envelope. In this scenario, one wonders why a T Tauri star would be surrounded by an optically thick envelope, since they are usually defined as objects around which the vast majority of the circumstellar material lies in an equatorial disk. It has been proposed that they are in fact deeply embedded because they are experiencing a temporary high accretion rate event similar to FU Ori bursts (Ghez et al. 1991, White & Ghez 2001) so that their opaque envelope would be a transient phenomenon. The number of IRCs would then suggest a relatively short-lived phenomenon (≈ 10^4 yrs). It remains to be understood how such an opaque envelope suddenly appears around one of the components of the system. This may be the result of star-star dynamics within the systems (Bonnell & Bastien 1992) but the details of this phenomenon still have to be described.

There is however one usual property of protostars that IRCs do not share: a vast envelope. Millimeter mapping has shown that protostars have envelopes thousands of AU in radius (e.g., Motte & Andrè 2001) whereas the fact that IRCs are in multiple systems imply that the outer radius of their envelope is not bigger than ~2–100 AU depending on the system. From this point of view, IRCs are unlikely to be actual protostars. By analogy, this implies that Class I objects in general, which are defined by their near- to mid-IR SED, should not be considered protostars without further analysis, even though they are not known to have a companion. In fact, as discussed in André et al. (2000), the presence of a massive and extended envelope is required to consider an object a bona fide protostar. With this criterion, none of the IRCs can be considered a real protostar and the apparent non-coevality of the systems is solved.

In summary, this study reminds us, from an unusual perspective, that a Class I-type SED is not the ultimate proof that an object is a protostar and that there might be a few non-coeval multiple systems in star-forming regions. If we take the Class I classification of IRCs from their SED at face value, we then consider these systems as not coeval and we must explain how they formed. One possibility is that IRCs formed after a gravitational instability disrupted the circumstellar disk of their companion. This could represent a secondary channel for star formation and, although it only amounts to a few percent of all the stars formed in an environment such as Taurus, it would be interesting to see if different star-forming regions can form more objects in this way. Alternatively, IRCs might be FU Ori-like objects as old as their T Tauri companion, in which case dynamical interactions within the systems would need to be
extremely strong. Finally, a more original scenario for explaining (some of the) IRCs is that they are high-mass objects extincted by a nearly edge-on disk. If so, this would imply that even the Taurus molecular cloud can form objects as massive \( \approx 5 M_\odot \). In any case, the unusual properties of IRCs deserve further investigation.

**Acknowledgments**

The authors are grateful to the organizers of the conference for its great atmosphere, highly interesting list of topics and professional organisation. Many thanks also to Hans Zinnecker, Nuria Calvet, Lee Hartmann, Bo Reipurth and Philippe André for enriching discussions following this presentation. This work has been supported by the National Science Foundation Science and Technology Center for Adaptive Optics, managed by the University of California at Santa Cruz under Cooperative Agreement AST 98-76783.

**References**

André, P., Ward-Thompson, D. & Barsony, M. 2000, in “Protostar & Planets IV”, eds. Mannings, Boss & Russell, Univ. of Arizona Press, p. 59
Beck, T., Prato, L. & Simon, M. 2001, ApJ, 551, 1031
Bonnell, I. & Bastien, P. 1992, ApJ, 400, 579
D’Alessio, P. et al. 1999, ApJ, 527, 893
Duchêne, G. et al. 1999, A&A, 351, 954
Duchêne, G., Ghez, A. M. & McCabe, C. 2002, ApJ, 568, 771
Duchêne, G. et al. 2003, ApJ, in press [astro-ph/0303648]
Dyk, H. M., Simon, T. & Zuckerman, B. 1982, ApJ, 255, L103
Feigelson, E. D. & Kriss, G. A. 1989, ApJ, 338, 262
Ghez, A. M. et al. 1991, AJ, 102, 2066
Hanner, M. S., Brooke, T. K. & Tokunaga, A. T. 1998, ApJ, 502, 871
Hartigan, P., Strom, K. M. & Strom, S. E. 1994, ApJ, 427, 961
Herbst, T. M., Koresko, C. D. & Leinert, C. 1995, ApJ, 444, L93
Koresko, C. D., Herbst, T. M. & Leinert, C. 1997, ApJ, 480, 741
Koresko, C. D. 2000, ApJ, 531, L147
Leinert, C. et al. 2001, A&A 369, 215
Loinard, L., Rodríguez, L. F. & Rodríguez, M. I. 2003, ApJ, 587, L47
Ménard et al. 2003, ApJ, submitted
Motte, F. & André P. 2001, A&A, 365, 440
Myers, P. C. et al. 1998, ApJ, 492, 703
Reipurth, B. 2000, AJ, 120, 3177
White, R. J. & Ghez, A. M. 2001, ApJ, 556, 265
Wood, K. et al. 2002, ApJ, 564, 887
Zinnecker, H. & Wilking, B. A. 1992, in “Binaries as Tracers of Stellar Formation”, eds. Duquennoy & Mayor, Cambridge Univ. Press, p. 269