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The Infrared Companions of T Tauri Stars: Clues to the Formation and Early Evolution of Binaries

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Abstract. Infrared companions are young stellar objects with unusual properties gravitationally bound to more or less typical T Tauri stars. As such they promise to be the source of information on either a particular phase in the development of young stars or on a particular mode of development. We discuss the observed properties of infrared companions as well as attempts to explain their physical status with the aim to see how much of solid conclusion has been obtained so far and what direction of further studies may be expected.

1. Introduction

In the most favored picture of binary and multiple star formation, the various stellar components are produced when a collapsing cloud core fragments under the influence of rotation, magnetic fields, and turbulence (*c.f.*, a number of papers in these conference proceedings). A basic prediction of this picture is that the stellar components of a binary or multiple system are coeval in the sense that evolutionary clocks are effectively synchronized at the beginning of their evolution along their pre-main sequence tracks. From that point onward, they evolve nearly independently at predictable mass-dependent rates determined by the physics of convection, nuclear burning, and radiative transfer in their interiors. A comparison of the evolutionary ages of the components of a given system at any time after its formation, using, *e.g.*, photometry and spectroscopy to place each component in an H-R diagram for comparison with theoretical pre-main sequence evolutionary tracks, or spectral energy distribution (SED) proxies such the Lada (1987) class or the bolometric temperature (Chen et al. 1995), should yield consistent results.

The pioneering work of Hartigan et al. 1994 showed that this prediction holds true for 2/3 of the 26 wide (projected separation 400 – 6000 AU) visual binaries which composed their sample. In the cases where there were significant age differences between the component stars, the less massive star was usually the younger. They found no correlation between the age differences and the presence or absence of accretion disks. More recent observations by Brandner and Zinnecker (1997) showed that all 8 of their sample of binaries with projected separations between 85 and 240 AU were consistent with coeval formation, leading them to suggest that the formation mechanism for a significant fraction of the wider pre-main-sequence binaries might be different from that of closer ones. Woitas & Leinert (2000) reach similar conclusions about a set of 17 weak-lined TTS (WTTS) binaries, although they also find some unusually red objects in a sample of the more extreme classical T Tauri stars (CTTS). Interestingly, they also derive a distribution of mass ratios which is independent of primary mass and binary separation, which they interpret as evidence for fragmentation as the dominant binary formation mechanism.

The red objects described by Woitas & Leinert (2000) are candidate members of a class of T Tauri companions which may present a significant challenge to the fragmentation picture. These objects are referred to as the "Infrared Companions" (IRCs). They radiate predominantly in the infrared, giving them a very youthful appearance which seems inconsistent with the ages of the stars they orbit. Although the combination of faintness at visual wavelengths and their modest angular separations from their visually-brighter "primary" stars makes most of the IRCs difficult targets for visual spectral classification, their bolometric temperatures lie at the lower extreme of the range of occupied by T Tauri stars, but above the true protostars (Koresko, Herbst, & Leinert 1997; hereafter KHL). Zinnecker & Wilking (1992) estimate that IRCs constitute perhaps 10% of all T Tauri binary companions detected in the binary surveys of Ghez, Neugebauer, & Matthews (1993) and Leinert et al. (1993). The samples in these studies contained primarily CTTS in the Taurus and Ophiuchus star-forming regions (SFRs). A list of several of the best examples of IRCs is given in Table 1.

The most basic question that will be addressed here is this: Are the IRCs truly stars with significantly younger evolutionary ages than their primaries, or are they more evolved (presumably coeval) objects whose appearance has been modified by some process which alters either the light they radiate or the stars themselves? If the latter, what are the implications of the existence of such a process for our understanding of the evolution of multiple stars, and for stars in general?

2. Properties of the Infrared Companions

While the IRC class is defined by bright infrared and faint visible radiation and the presence of a T Tauri primary, a multitude of observations over the years since the discovery of the first IRC (the T Tauri IRC, by Dyck, Simon, & Zuckerman 1982) have identified a number of other unusual and perhaps characteristic features of these objects. For the most part, these features tend to be more extreme versions of phenomena seen in more "normal" T Tauri stars, such as infrared excesses, photometric variability, and shock-excited emission lines of molecular hydrogen. Other features such as rapidly-changing nonthermal radio emission seem to be more or less unique to the IRC class among the CTTS or even to specific IRCs. Here we discuss these features in some detail.

Table 1. Selected Infrared Companions

System	Discovered	by	Technique
UY Aurigae	1944	Joy & van Biesbroek	Visible Image
T Tauri	1982	Dyck, Simon, & Zuckerman	IR speckle
VV CrA	1985	Frogel	IR offset
DoAr 24e	1988	Chelli et al.	IR speckle
Glass I	1988	Chelli et al.	IR speckle
Haro 6-10	1989	Leinert & Haas	IR speckle
XZ Tauri	1990	Haas, Leinert, & Zinnecker	IR speckle

2.1. Infrared Excess and Bolometric Temperature

It is useful to examine scalar quantities which can be calculated from the SED to estimate the importance of the infrared excess in an IRC. Here we examine two such quantities which have been applied in the literature to various young stellar objects. A comparison of the value of each of these quantities measured for the IRCs suggests that their IR excesses are intermediate between those of the reddest classical T Tauri stars and true embedded objects.

The simplest of these quantities is perhaps the fraction $L_{\rm IRAS}/L_{\rm bol}$ of the object's total luminosity which emerges in the IRAS passbands at wavelengths between 12 and 100 μm. For even a very cool stellar photosphere, this ratio is less than 0.01, while for stars which are "embedded" according to the definition of Kenyon, Calvet, & Hartmann (1993) it is at least 0.8. This latter value corresponds to a blackbody temperature of 220 K. The IRCs studied by KHL do not quite reach this degree of "embeddedness", having $L_{\rm IRAS}/L_{\rm bol}$ between 0.18 (for DoAr 24E IRC) and 0.76 (for Haro 6–10 IRC).

The bolometric temperature $T_{\rm bol}$ is defined as the temperature of a blackbody having the same mean frequency (essentially the "center of mass" of the SED) as the observed continuum spectrum (Myers and Ladd, 1993). A plot of $L_{\rm bol}$ versus $T_{\rm bol}$ has the same main sequence as the H-R diagram, and $T_{\rm bol}$ has been found to correlate well with the apparent evolutionary status of pre-main sequence stars, being higher for more evolved classes of objects. Myers and Ladd (1993) show that young low-mass stars in such a plot tend to be segregated into regions according to their observational "types", *i.e.,* weak-lined TTS, classical TTS, protostar-TTS, and protostars. Chen et al. (1995) found that the standard classification scheme for YSO spectral energy distributions (Lada & Wilking 1984; Wilking, Lada, & Young 1989; André, Ward-Thompson, & Barsony 1993) corresponds to distinct ranges of $T_{\rm bol}$, with $T_{\rm bol} = 70$ K for Class 0, $T_{\rm bol} = 70 - 650$ K for Class I, $T_{\rm bol} = 651 - 2880$ K for Class II, and $T_{\rm bol} = 2880$ K for Class III. Class 0 corresponds to truely embedded objects; classes I-III have been identified with protostellar objects, classical T Tauri stars, and weak-lined T Tauri stars, respectively (Adams, Lada, & Shu 1987). The bolometric temperatures of the sample of IRCs studied by KHL range from 210 to 800 K, and are clustered approximately midway between those of the warmest embedded sources and the coolest CTTS.

2.2. Primary Stars

The IRCs are by definition associated with more or less "normal" T Tauri stars, which in practice are usually $\sim 10^6$ yr old CTTS with significant infrared excesses

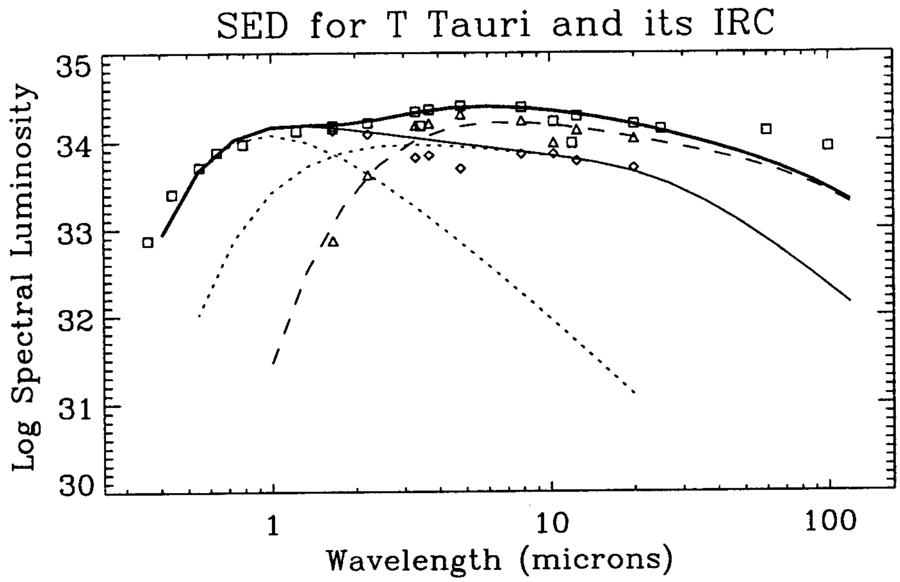

Figure 1. The spectral energy distributions for the components of the T Tauri system are plotted along with with simple models. The two dotted curves correspond to the photosphere and disk of the primary, and the thin solid curve traces their sum. The dashed curve is an empirical fit to the SED of the IRC, and the heavy solid curve is the sum of all components. Photometric data points are plotted with points. The squares trace the total flux of the system, while the diamonds and triangles mark the fluxes of the primary and IRC, respectively. Both stars have large infrared excesses, but the primary dominates at wavelengths shorter than 2 μm while the IRC dominates at longer wavelengths. The data and models are from KHL and references therein.

of their own. For the present, we will refer to these visibly-bright stars as the "primaries" regardless of their relative bolometric luminosities, following the convention of KHL.

2.3. Spectral Properties

The availability of visible-light spectra of IRCs is limited at present because of their faintness and proximity to primaries which are much brighter at visible wavelengths. The Glass I IRC is an exception, perhaps because it was in visually-bright phase at the time of the spectral observations. Feigelson & Kriss (1989) obtained visual spectra of the primary and the IRC, for which they estimated spectral types of K3 and G5e, respectively. And Reipurth and Zinnecker (1993) in their imaging survey for young binaries, found the Glass I IRC to be nearly as bright as the primary in the Gunn z filter.

Unlike the visual spectra, infrared spectral information (albeit at low resolution) is relatively plentiful. Herbst, Koresko, & Leinert (1995) obtained R $\sim$ 250 spectra in the K (2.0 – 2.4 μm) band of the primaries and companions in the UY Aurigae and Haro 6–10 system. They found that the primary stars displayed normal photospheric absorption features roughly consistent with the temperatures determined from visible-light spectra, together with the Brγ emission line of atomic hydrogen which is common in T Tauri stars. The spectrum of the UY Aurigae IRC was similar to that of its primary star except for the presence of a v = 1–0 S(1) emission line of molecular hydrogen, while the Haro 6–10 IRC displayed only a red continuum which was featureless except for the same molecular hydrogen line.

A number of additional IRCs have been studied using narrowband filter sets, mainly centered on the silicate feature at 10 μm, the ice feature at 3.1 μm, and the v = 1–0 S(1) molecular hydrogen line at 2.12 μm. In general, the IRCs are more interesting than their primaries at these wavelengths, with the solid-state features pointing to strong circumstellar extinction and the molecular emission to the presence of low-velocity shocks.

Mid-infrared spectra of the IRCs orbiting T Tauri and Haro 6-10 (Ghez et al. 1991; van Cleve et al. 1994; Herbst, Robberto, & Beckwith 1997) showed deep 10 μm silicate absorption features which are not seen in their primaries, indicating that they suffer strong extinction due to localized dust distributions. The T Tauri primary appears to show the same silicate feature in *emission*. Herbst, Robberto, & Beckwith (1997) found that the shapes of the silicate features in both the primary and the IRC could be reproduced with a model in which each star is surrounded by a disk which has tenuous upper layers of varying emissivity and density.

It cannot be said that the water ice absorption feature at 3.09 μm, which is well correlated with visual extinction A_V (Whittet et al. 1988), is unusually common in infrared companions. But in Haro 6-10 (alias Elias 7) Whittet et al. (1988) found strong ice band absorption. It was an independent confirmation for the large amount of circumstellar dust around the infrared companion in this binary that spatially resolved observations (Leinert et al. 1996; Beck et al. 2000; Leinert, Ligori, & Woitas 2000) showed the ice feature to be concentrated on the companion.

2.4. Photometric and Spectral Variability

Strong photometric variability appears to be common, and perhaps universal, among IRCs. At least five IRC systems are known to exhibit photometric variations. The T Tauri IRC went through an outburst between 1989-91 in which it brightened by $\sim$ 2 magnitudes between 2 and 10 μm (Ghez et al. 1991; Kobayashi, et al. 1994; Simon et al. 1996), and the brightness ratio of the IRC systems UY Aurigae, Haro 6-10, Do-Ar 24E, and VV CrA have also been observed to vary substantially in the near-infrared (see KHL and references therein). The most extreme example known at present is UY Aurigae, whose IRC was originally discovered as a visible star only 0.5 mag fainter than its primary (Joy & van Biesbroeck 1944). Half a century later, a much more sensitive R-band CCD image failed to detect the object at all, indicating that the IRC had become at least 5 magnitudes fainter than the primary (Herbst, Koresko, & Leinert 1995). The object was rediscovered as an IRC by Tessier, Bouvier, & Lacombe (1994) based on a December 1990 speckle measurement in the L' (3.8 μm) photometric band. Speckle brightness ratios were measured by Leinert in the J, H, and K bands from December 1990, and in the L' and M bands from September 1991, which confirm the IRC nature of the object. The 1990 and 1991 measurements at L' are consistent with each other. However, speckle brightness ratio measurements made in the J, H, and K bands in October 1994 by KHL indicate a significantly warmer near-IR color temperature for the IRC in 1994 compared to 1990.

The IRC system with the best-sampled light curve is probably Haro 6–10, with photometric monitoring available (Leinert, Ligori, & Woitas 2000; Beck et al. 2000) with sufficient angular resolution to derive the brightness of the IRC at near-infrared wavelengths over a total timespan of more than a decade, unresolved near-infrared photometry of the system being available for another 14 years. Both the primary and the IRC exhibit significant and irregular variability in both brightness and color across the near-infrared region, with the IRC's variability being generally larger than the primary's. The overall brightness of the system in the K (2.2 μm) band has fallen by nearly an order of magnitude since 1975, and the IRC has varied nominally by factors of of up to 5 on timescales of months, but the accuracy of flux determination is comparatively poor in the times when the companion is faint. A large event seems to have begun in approximately 1996, during which the primary's flux has fallen by 2 mag while the IRC's has risen, and in particular the primary became redder. On the date of the most recent observations, the K-band brightness ratio had reversed, with the IRC becoming the brighter object. Apart from this event, the colors of the stars usually seem to be unrelated to the brightness of the primary, and the variations of the two stars are usually uncorrelated with each other. This leads Leinert, Ligori, & Woitas (2000) to conclude that one single mechanism such as changes in reddening is inadequate to explain the observed behavior of the system.

Variations in the ice feature of Haro 6-10 perhaps provide the most direct clue to the varying distribution of dust in this binary with infrared companion. So far, no clear picture has yet evolved from these observations (Beck et al. 2000; Leinert, Ligori, & Woitas 2000). A simultaneous or near-simultaneous measurement of indicators for infall (H_2 emission) and extinction (colour, ice feature, silicate absorption) with varying brightness of the components may be needed to help clarify the processes which make Haro 6-10 north an infrared companion.

The T Tauri IRC is also quite variable. As mentioned above, it went through an outburst between 1989-91 in which it brightened by ~ 2 magnitudes between 2 and 10 μm. Roddier et al. (2000) found that the magnitude difference between the primary and IRC in the K band changed from 2.6 on Christmas 1994 to 0.6 in November 23, 1999, and monitoring by Beck et al. (2000) over a two-year period ending in January 2000 showed changes as large as 50% in its K-band flux measured on dates only a few days apart. By contrast with the IRC and also with the Haro 6–10 primary, the T Tauri primary appears to be relatively stable during the Beck et al. (2000) period.

The brightness ratios of the IRC systems UY Aurigae, Do-Ar 24E, and VV CrA have also been observed to vary substantially in the near-infrared (Graham 1992; KHL).

2.5. Infrared Morphology

In recent years the angular resolution available for near-infrared imaging observations has been improved significantly due to the development of speckle and adaptive optics capabilities for telescopes with apertures as large as 10 m. These facilities have made it possible to begin to resolve structure in some of the IRCs, and thereby directly test some of the models.

The most-studied object so far is the T Tauri IRC. A series of careful observations using adaptive optics first confidently detected resolved structure in this object, which was initially interpreted as being due to circumstellar material such as a disk (Roddier et al. 2000). Later speckle holographic observations with higher resolution resolved the object into a pair of pointlike stars separated by $0''.05$, corresponding to a projected separation of 7 AU at the distance to the Taurus SFR (Koresko 2000). Followup adaptive-optics compensated speckle interferometry (AOCSI) observations have detected a change in the separation and position angle of the IRC double which is consistent with orbital motion (Köhler, Kasper, & Herbst 2000). Both stars must be highly reddened to account for the low upper limit on the total flux set by Hubble Space Telescope observations at visible wavelengths (Stapelfeldt et al. 1998).

Because a binary system is expected to truncate any disks around its components to $\sim 1/3$ of their orbital separation (Lin & Papaloizou 1993; Artymowicz & Lubow 1994) the radii of circumstellar disks in such a binary should be no more than a few AU in size. Standard models for pre-main sequence disks have power-law surface densities which place the great majority of the mass at larger radii. Thus the duplicity of the T Tauri IRC may explain why, despite the large extinction, submillimeter images place upper limits on its circumstellar dust mass no more than 3×10^{-3} $M_\odot$, which is well below the mass of the disk around the primary star (Hogerheijde et al. 1997; Akeson et al. 1998).

As has turned out to be the case in many other areas, the duplicity of the IRC in the T Tauri system seems to make it more atypical than prototypical. In contrast, holographic observations of the Haro 6–10 IRC revealed a bright, compact, nebulous object which shows no sign of duplicity (Koresko et al. 1999). Rather, it appears to be a star surrounded by an irregularly-shaped dusty envelope, which might perhaps outline the outer regions of a circumstellar disk which has been disrupted by infalling material or the gravitational influence of the primary star. Similarly, holography of the IRC in the VV CrA system has detected an extended envelope which contributes $\sim$ 10% of the total light at 2.2 μm, and no evidence for a tertiary companion (Koresko et al. 2001). Finally, holographic observations of the IRCs of Do-Ar 24E, UY Aurigae, and WSB 4 show no sign of extended structure at all (Koresko et al. 2001).

2.6. Radio Emission and Circumstellar Matter

In a seminal study, Beckwith et al. (1990) surveyed a sample of 86 T Tauri stars in the radio continuum at 1.3 mm, with the goal of detecting and measuring the thermal emission from dust in circumstellar disks. At these wavelengths, the disks are expected to emit mostly in the optically-thin regime, so that the flux is directly proportional to the disk mass, in contrast to the infrared emission which is likely to be optically thick.

The submillimeter survey sample included the IRC binaries T Tauri, UY Aurigae, and XZ Tau. These systems do not stand out among the sample as having unusually large dust masses. In particular, the dust masses are always small compared to the stellar masses, confirming that the IRCs have evolved beyond the phase in which their masses grow significantly via accretion. As noted above, more detailed studies of the T Tauri system have revealed that the mass of dust surrounding the IRC is actually significantly smaller than that surrounding the primary star.

Although a number of pre-main sequence stars are radio emitters (*e.g.*, Chiang, Phillips & Lonsdale 1995 and references therein), the T Tauri IRC is one of only two known pre-main sequence sources of circularly polarized nonthermal radiation at centimeter wavelengths (Phillips et al. 1993; Skinner & Brown 1994), the other being the Class 1 protostar IRS 5 in the Corona Australis "Coronet Cluster" (Feigelson, Carkner, & Wilking 1998). This observation hints at the action of some unusual energetic process, perhaps accretion-driven, involving strong magnetic fields.

2.7. Giant Flows

The T Tauri and Haro 6–10 IRCs are believed to drive giant Herbig-Haro flows which have been seen to extend over distances of $\sim$ 1.5 pc, pointing toward rapid accretion in these objects.

The North-South jet associated with the T Tauri IRC lies only $\sim$ 11 deg from the plane of the sky (Solf & Bohm 1999). This jet, which has apparently been traced over a distance of $\sim$ 1.5 pc in a giant Herbig-Haro flow (Reipurth, Bally, & Devine 1997) is nearly perpendicular to the jet from T Tauri N, whose axis lies close to the line of sight and has an East-West sky-projected direction. This suggests that the axes of the circumstellar disks which are presumably powering the jets are likely to be strongly misaligned in the T Tauri system.

A giant Herbig-Haro flow from the Haro 6–10 system was found by Devine et al. (1999). This flow extends about 1.6 pc (39 arcmin) along a position angle close to 222°. The discoverers suggest that the flow originates from the IRC, which they assume to be in an earlier evolutionary state than the primary. The giant flow may trace the outer regions of a more compact jet first reported by Movsessian & Makagian (1999) and also seen in infrared images by Koresko et al. (1999) and Leinert, Ligori, & Woitas (2000). The smaller jet curves away from the Haro 6–10 binary at a position angle of 195°. It is not yet completely clear whether the IRC or the primary star is the driving source.

3. The Nature of the IRC Phenomenon

A number of questions arise immediately when one considers the observational data on IRCs. Are these objects fundamentally different from their primary stars, with their infrared excesses and activity pointing to an evolutionary phase younger than the T Tauri stars, or do their youthful outward appearances hide more mundane central stars? Do the IRCs represent a single physical phenomenon whose origins are common to most or all of them, and perhaps tied to a particular point in their evolution toward the main sequence, or are they a diverse collection of objects which happen by accident to share certain observational characteristics? If the former, is there an "IRC phase" which most or all T Tauri stars in binaries go through at some point in their evolution, or does the IRC phenomenon occur only for some specific range of stellar parameters and environment? Is there a favored binary separation range? What about single T Tauri stars? If the IRCs are episodic accreters, how long do the episodes last, how many will occur during the pre-main sequence lifetime of the star, and how much mass is gained during these episodes?

We are not yet in a position to decide with confidence and in detail between these or other possibilities. But it does make sense to begin attempting to answer a few of the basic questions about the nature of the IRCs, and to explore the extent to which current observational data can be used to suggest, if not prove, what the answers might be.

3.1. Are the IRCs Coeval with their Primaries?

The standard approach to estimating the age of a pre-main sequence star is to compare its luminosity and effective temperature with those of theoretical models. The consistency of the ages of the components in the majority of pre-main sequence binaries studied this way suggests that this approach generally work fairly well. Unfortunately, the combination of large and possibly anisotropic extinctions, infrared excesses, variability, and faintness at the visible wavelengths for which spectral classification is most mature, have made it difficult or impossible to derive reliable age estimates for the IRCs.

Despite these difficulties, a few attempts have been made to determine IRC ages, or at least to make plausibility tests for coevality with the primaries, with results that seem to support coeval formation. KHL *assumed* coevality and placed each of the six IRCs in their sample on an H-R diagram to derive estimates for their effective temperatures. The result for the Glass I IRC was consistent with the G5e spectral type estimated by Feigelson & Kriss (1989) from a visible-light spectrum taken in 1981, when the IRC was a visible CTTS with m_V = 14.09 (it is not known whether the IRC remained observable at visible wavelengths at the time was found to be an IRC).

For the UY Aurigae IRC, KHL found effective temperatures corresponding to a spectral type of K6 and K7 for data from 1990 and 1994, respectively, which is roughly consistent with the M0 roughly estimated from the low-resolution near-infrared spectrum of HKL. Close et al. (1998) fit models of extincted stars surrounded by warm disks to the SEDs of UY Aurigae and its IRC, and found that they could be fit with a common age of 3×10^5 yr and HKL's spectral types of K7 and M0.

We can conclude from this that the first, tentative steps toward real age estimates suggest that the IRCs may be coeval with their primaries. But a need for caution is indicated by the fact that the UY Aurigae IRC is apparently "new" to the class, and the Glass I IRC may also be, with its relative brightness at visual wavelengths two decades ago being somewhat surprising in light of the shape of its SED at infrared wavelengths.

3.2. Special Viewing Geometries

Perhaps the simplest model for producing the large extinction in an IRC would be a special arrangement of the system's geometry such that the IRC is hidden behind normal disk material around the primary or the IRC itself. In this picture, the IRCs could be intrinsically quite similar to their primaries. Here we briefly discuss two models that have been proposed in the literature.

The IRCs could be surrounded by circumstellar disks viewed nearly edge-on. The extinction would be produced by the material in the outer disk, which is perhaps inhomogeneous so that the dust column varies significantly as orbital motion carries different parcels of mass through the line of sight.

Two objections to this model may be raised by comparison with the known edge-on disk system HK Tauri B. First, none of the images show the clean, 100 AU disk structure evident in, the companion to HK Tauri (Koresko 1998). This centrally-brightened double-lenslike structure traces starlight scattered above and below the disk plane, which is itself quite dark. For the unresolved IRCs, the images require edge-on disks to have scattering regions smaller than ~ 5 AU in diameter. The second objection is that in the known edge-on disk system, the star and the hot inner disk, which should be the source of much of the near through mid-infrared excess emission, are occluded by the cool outer disk, and visible only in scattered light. As a result, the shape of the system's SED is more reminiscent of a moderately-extincted star than of an IRC. However, it is still possible that certain combinations of small disk mass and orientations not quite edge-on can reproduce the observations. Detailed radiative-transfer modeling is needed to fully test these possibilities.

A second possibility is that the IRCs lie behind the disks associated with their primary stars, as has been suggested for the T Tauri system (*e.g.,* van Langevelde et al. 1994). As noted by Akeson et al. (1998), although the radius of the T Tauri N disk appears smaller in their submillimeter images than the distance to the IRC, submillimeter imaging cannot rule out the existence of a more diffuse outer disk such as that proposed by Hogerheijde et al. (1997).

3.3. Disk Accretion

It has been proposed that the origin of the large and variable infrared excess in the T Tauri IRC is an active accretion disk (Ghez et al. 1991). This is sometimes referred to as the "mini-FUor" model, after its similarity to the FU Orionis class of objects which are believed to be T Tauri stars whose disks are undergoing episodes of very rapid accretion. The IRCs would be considerably less extreme cases, in which the luminosity due to the disk is never very much larger than that of the stellar photosphere.

The mini-FUor model was elaborated on by KHL, who suggested that the accretion could be triggered by gravitational interactions, and synchronized with the orbital phase, if the binary orbits are eccentric. A particularly interesting possibility is that the IRC phenomenon is both triggered and fueled by streams of matter coming from a circum*binary* disk, as predicted by hydrodynamical models Artymowicz & Lubow, 1996. Unfortunately, while the molecular hydrogen line emission found in the IRCs to T Tauri, UY Aurigae and Haro 6–10, and the unusual radio emission in the T Tauri IRC, point to the action *some* energetic process in these objects, it is difficult to demonstrate conclusively that disk accretion is responsible for producing their characteristic SEDs.

3.4. Episodic Accretion

One can make some very crude and unreliable estimates of the frequency and duration of a typical IRC event in the recurrent "episodic accretion" picture in the following way: Starting with the estimate that 10% of the companions of classical T Tauri stars are IRCs (Zinnecker & Wilking 1992) and the assumption that these episodes occur periodically with constant frequency and duration for all CTTS companions throughout a typical pre-main sequence lifetime of 10^6 yr, one finds that each object spends a total of 10^5 yr as an IRC. If exactly one among the half dozen or so well-studied IRCs has changed state from non-IRC to IRC in the last $\sim$ 25 yr, then for each object these transitions occur on timescales of $\sim$ 150 yr. Considering the crudeness of this calculation, this timescale is more or less consistent with the orbital timescale of $\sim$ 700 yr for a pair of solar-mass stars separated by 100 AU.

Suppose that the infrared luminosity of an IRC is produced by accretion of diffuse matter from a disk or envelope. The infall of 10^{-7} $M_\odot$ yr^{-1} of gas onto a solar-mass star of radius 3 $R_\odot$ would be required to produce the 1 $L_\odot$ typical of an IRC's infrared excess. At this rate, and using the above estimate for the total time spent as an IRC, a typical T Tauri companion would accrete 10^{-2} $M_\odot$. As required by the submillimeter photometric observations, this mass is small compared to the mass of the star, although it is somewhat larger than the mass of material surrounding the T Tauri IRC. It is suggestively comparable to the mass of a typical pre-main sequence disk.

It has been shown (Hartmann & Kenyon 1990) that accretion rates comparable to the photospheric luminosity can alter the contraction of a young star toward the main sequence. Although this is likely to occur for the IRCs during their active accretion phase, the relatively low duty cycle probably prevents it from having a very important effect over the long term.

Clearly, these results do not demonstrate the validity of the recurrent episodic-accretion picture for the IRCs, but they do show that it is not grossly inconsistent with the observations.

3.5. Binary Separations

The angular separations between the known IRCs and their primaries are typically between $0''.3$ and $3''.0$, corresponding to projected linear distances of $\sim 40 - 400$ AU. These distances are close to the fiducial size of a circumstellar disk, suggesting that star/disk interactions might play a role in triggering and/or fueling the IRC phenomenon. Unfortunately, the significance of this distance may be obscured by observational effects: Historically, it has been difficult to measure the photometric fluxes of individual stars with separations smaller than this range, and at separations a few times larger it becomes uncertain whether the two stars form a true binary pair. The separation range of the known IRC binaries may therefore be strongly biased by selection effects.

3.6. Dissipating Triple Systems

It has recently been proposed that the IRCs may be members of dissipating, non-hierarchical triple systems (Reipurth 2000). In this picture, the young triple would be surrounded by a surrounding dusty envelope whose column density is large enough to strongly extinct and redden the stars closest to its center. As the orbit of the triple system evolves, two of the three stars move into a strongly bound orbit while the third is either thrown into a loose orbit or ejected completely. The tightly-bound pair typically contains most of the mass of the system, and it therefore tends to remain close to the center of the envelope and suffers strong extinction, while the less-massive object suffers less.

This picture leads to a number of predictions which should be testable in principle. For one thing, it demands that at least three stars be present in every IRC system, and most of the IRCs will be close doubles. Further, they should tend to dominate the system's bolometric luminosity both because of their duplicity and because their accretion rates are likely to be enhanced. They will be photometrically variable because of the perturbations to their accretion disks and because of the changing extinction as they pass through the cloud. If the center of mass of the system of stars is close to that of the envelope, then the more reddened object will tend to be the receding one, and we should see a redshift of the IRC relative to the visible primary.

Reipurth (2000) compares this model to the T Tauri system, and finds that it explains many of the features. The exception is the observation by Hogerheidje et al. (1997) and Akeson et al. (1998) that most of the diffuse mass is associated with the visible primary rather than the IRC. Reipurth (2000) suggests that this may reflect the more rapid depletion of the circumstellar disks in the IRC.

4. Future Investigations

The IRCs were relatively challenging observational targets at the time that the T Tauri IRC was discovered. Their separations are typically not large compared to the seeing limit of a telescope at a moderately good site, requiring both special instruments and techniques. They were typically discovered using one-dimensional slit-scans in the near-infrared. But the last two decades have seen very substantial improvements in instrumentation and techniques, with the development of improved telescope optics, better speckle imaging using array detectors, adaptive optics, and sensitive infrared spectrographs. In addition, spectral standards have become available for the near-infrared, making it practical to estimate effective temperatures for IRCs too faint to observe at visible wavelengths. Taken together, these developments should enable rapid progress toward a more mature understanding of the IRCs.

Several photometric monitoring programs are currently ongoing. Once a sufficient database has been accumulated it will be interesting to consider the *timescale* of the variations as well as their magnitude. In principle, this timescale may strongly constrain the mechanism responsible for the changing flux. In particular, if one believes that the changes are due to the motion of masses of extincting and/or scattering material which is either orbiting the star or falling in from infinity, then the speed at which those masses move, and hence the involved time scales, may be crudely estimated as the freefall speed at their distance from the star. The timescale of the variability is then given by the ratio of the size of the occulting masses to this speed.

In the near future, systems combining adaptive optics on large telescopes with AO-optimized infrared spectrographs (*e.g.,* NIRSPEC on Keck 2) will make it possible to obtain near-infrared spectra of IRCs with both high spatial and spectral resolution. Such spectra will likely allow several IRCs to be spectrally classified even when they are too faint to be observed visually. It may be also be possible to use the depth of the photospheric absorption lines to derive an estimate for the infrared "veiling", *i.e.,* the fraction of the light produced by non-photospheric sources such as thermal radiation by circumstellar dust, providing more or less direct estimates of the photospheric luminosities and mass accretion rates. This information will allow IRCs to be placed more confidently on the H-R diagram, greatly clarifying their evolutionary status. High resolution spectra may also be used to search for the double-peaked line profiles characteristic of emission by a disk photosphere, providing a clean test of the accretion mechanism. Furthermore, if the spectral resolution is sufficiently high, it may be possible to search for the redshifts predicted by the dissipating-triples model.

Finally, it has been noted (Koresko 2000) that the orbit of the two stars in the T Tauri IRC has a period of only a decade or so. This raises the possibility that a complete orbit determination including masses and eccentricity can be derived on a timescale compatible with a graduate student thesis, by combining the visual orbit from speckle interferometry with velocity information from infrared spectra.

5. Implications for the Formation and Evolution of Binary Stars

At the present time, the existence of the IRCs, whose ages are possibly inconsistent with coeval formation, represent a potential challenge to the fragmentation scenario for the formation of binary stars. However, this challenge appears to be muted by the fact that the two IRCs whose ages have been studied seem consistent with their primaries. It now seems likely that the IRC phenomenon neither demands nor produces large deviations from normal pre-main sequence evolution. This tentative conclusion will need to be reexamined as improved observations become available.

On the other hand, it is very likely that the interactions between stars and disks in binary systems will have profound effects, if not on the stars, then on the disks and whatever planetary systems may come into being as they dissipate. The IRCs, with their large infrared excesses and other signs of unusually strong activity, may ultimately be tracers of these interactions, and their study an important means to understanding how planets may evolve in the most common stellar environments: binary stars.

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