My Favorite Object

T Tauri

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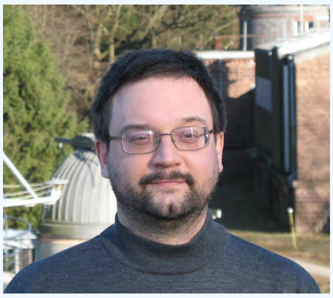

Figure 1: T Tauri (the orange star in the center) and Hind's Nebula. The field of view is $16' \times 16'$. North is up and east to the left. (Image by T. A. Rector/University of Alaska Anchorage, H. Schweiker/WIYN and NOAO/AURA/NSF)

Introduction

Every astronomer knows (or at least should know) the system T Tauri, since it gave its name to the whole class of young stars. Over the centuries, better observational techniques enhanced our knowledge of the system, often only to show that it is more complex than previously thought. With every new discovery made, it turned out to be more prototypical than typical for T Tauri stars.

T Tauri was discovered in November 1852 by John Russell Hind (Hind 1864). Using a 7-inch refractor (quite a large telescope at the time), he noticed a variable nebula in Taurus (now known as Hind's nebula, NGC 1555 or HH 155). In a side note, he mentioned that the star at the edge of the nebula is also variable. A few years later, this star was named T Tauri, because it was the third variable star discovered in Taurus (the first variable star in a constellation is denoted R, the second S, and so on).

Between 1867 and 1916, the visual brightness of T Tauri fluctuated randomly between 9.6 mag and 13.6 mag on time scales as short as a month (Lozinskii 1949; Beck & Simon 2001). Beck & Simon (2001) find that variable extinction along the line of sight is the most likely explanation for the observed fluctuation. In 1918, this kind of variability stopped abruptly, except for brief dimming events in 1925 and 1931. Between 1986 and 2003, T Tauri showed only low-level variability with an amplitude of 0.22 mag in V (Grankin et al. 2007).

In 1945, Alfred H. Joy proposed the new class of "T Tauri variable stars" based on their similar physical characteristics (Joy 1945). The name was chosen because T Tauri was the best known member of the group, one of the brightest, and its spectrum was also representative for the group. If the brightness of T Tauri had been as stable in the 19th century as it is now, it might not have been discovered so early, and the class of T Tauri stars might have been named differently.

It was soon suggested that T Tauri stars are solar-type stars in the early stages of formation (Ambartsumian 1947). Since that time, this has been generally accepted and became essentially the definition of the class (Herbig 1962).

As the prototype and one of the brightest members of the class, T Tauri has been and still is observed frequently, and many publications have been written about it. At the time of this writing, Simbad lists 1122 references (and it does not even include anything before 1895). I read about 1% of those papers and skimmed through another 2%, so I want to apologize in advance if I missed anything important.

A binary...

In 1981, Mel Dyck et al. observed T Tauri with the new observing technique of infrared speckle-interferometry (Dyck 1982). They were quite surprised to find that it is a binary. Today, it is generally accepted that most T Tauri stars are multiple systems, but back then, T Tauri lived up to its role as prototype. Dyck et al. had only an InSbphotometer that scanned the target in north-south direction. Luckily for them, T Tau N and S, as the two stars are called, are oriented almost exactly in that direction, with a separation of about 0.6″. They observed at three different wavelengths (2.2 μm, 3.8 μm, and 4.8 μm) and noted that the colors of the two stars are very different. Bertout (1983) suggested that T Tau S is a protostar of 2 to 3 $M_\odot$, obscured by 8 to 19 mag of visual extinction.

T Tau S is so red that it has never been detected at visual wavelengths. Stapelfeldt et al. (1998) found no trace of it in HST-images with a limiting magnitude of V = 19.6 mag. Therefore, it became the prototype for the so-called infrared companions (IRCs), companions to young stars that are much brighter in the infrared than at optical wavelengths (Koresko et al. 1997). The most likely explanation for this phenomenon is that IRCs are normal young stars hidden behind circumstellar dust, e.g. an accretion disk seen edge-on.

. . . or a triple

In the 1980s and 1990s, bigger telescopes and better instruments were built. With the Keck telescope and the good seeing on Mauna Kea, T Tau N and S could be resolved with direct imaging, without any special methods to enhance the spatial resolution. Chris Koresko used the opportunity and applied speckle interferometry to T Tau S alone. It turned out that T Tau S is also a binary, with a separation of 53 milli-arcsec at the time (Koresko 2000). This makes T Tauri a triple system consisting of T Tau N, T Tau Sa, and T Tau Sb.

The second resolved observation of T Tau Sa/Sb (Köhler et al. 2000) showed that the position angle had changed by 28° in only two years. It was clear that this binary has a rather short period, which will allow to determine its orbit within a reasonable time span (less than the lifetime of its observers).

However, Loinard et al. (2003) claimed that T Tau Sb had suffered an ejection during the close encounter with Sa around 1996. According to their data, the orbit of T Tau Sb had changed dramatically. T Tau Sb might even be leaving the system altogether. This would be the first time such an event had been observed, and caused a lot of interest in the orbit of T Tau Sb. The observations of Loinard et al. were carried out with the VLA at 2 and 3.5 cm wavelength. In the radio regime, T Tau is a double source, separated by about 0.7″ in north-south direction. It is clear that the northern radio source is the star T Tau N. The southern radio source was coincident within the errors with the position of T Tau Sb in an infrared image taken almost simultaneously. This led to the conclusion that the radio source is identical to T Tau Sb. T Tau Sa does apparently not contribute significantly to the radio signal, since the southern radio source was never resolved into a binary. Therefore, the motion of the radio source T Tau Sb had to be derived from precise astrometry relative to T Tau N.

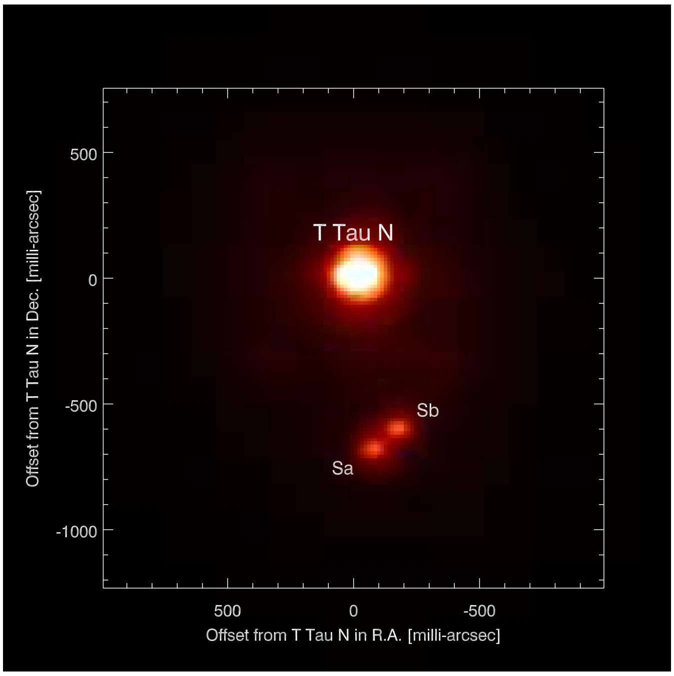

Figure 2: Image of the T Tau system taken with VLT/NACO in the K_s filter on 2008 February 1, shown with a logarithmic scale.

The interest in the orbit of T Tau S was met by new adaptive optics systems at large telescopes, which allowed to take resolved infrared images of all three components in the system (Fig. 2). With these instruments, T Tauri was observed quite frequently and a lot of astrometric measurements were collected (Duchêne et al. 2002, 2005; Furlan et al. 2003; Beck et al. 2004; Mayama et al. 2006; Schaefer et al. 2006; Köhler et al. 2008; Köhler 2008; Schaefer et al. 2013, 2014). The latest measurements and orbit determination were presented at the Protostars & Planets VI conference (Fig. 3). They show no sign of T Tau Sb escaping from the system or even being on a highly eccentric orbit. The most likely explanation is that the radio source is connected with, but not identical to the infrared source (Johnston et al. 2004a,b; Loinard et al. 2007a).

A nice result of the precise astrometry achieved with radio observations, however, is the measurement of the distance of the T Tauri system, which is 146.7 ± 0.6 pc (Loinard et al. 2007b). This is one of the most precisely known distances to any T Tauri star, since most of them were too far away for the Hipparcos satellite.

The presence of the third component gives us the rare op-

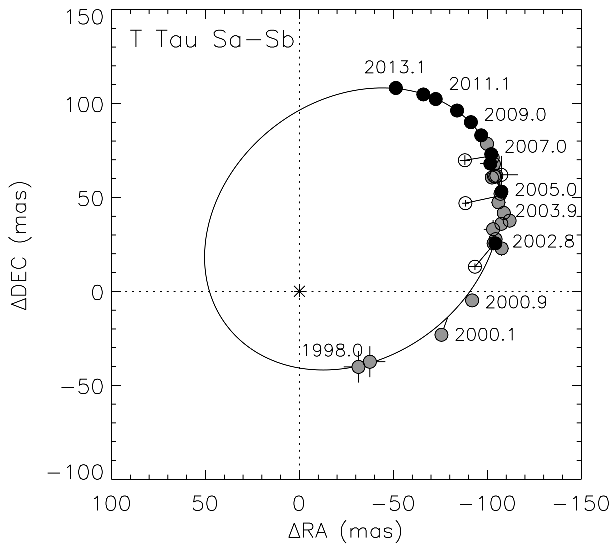

Figure 3: Orbital motion for T Tau Sa-Sb. Black circles are NIRC2 measurements. Gray circles are measurements with other instruments. Overplotted is the best fit orbit with a period of 28 yr (from Schaefer et al. 2013)

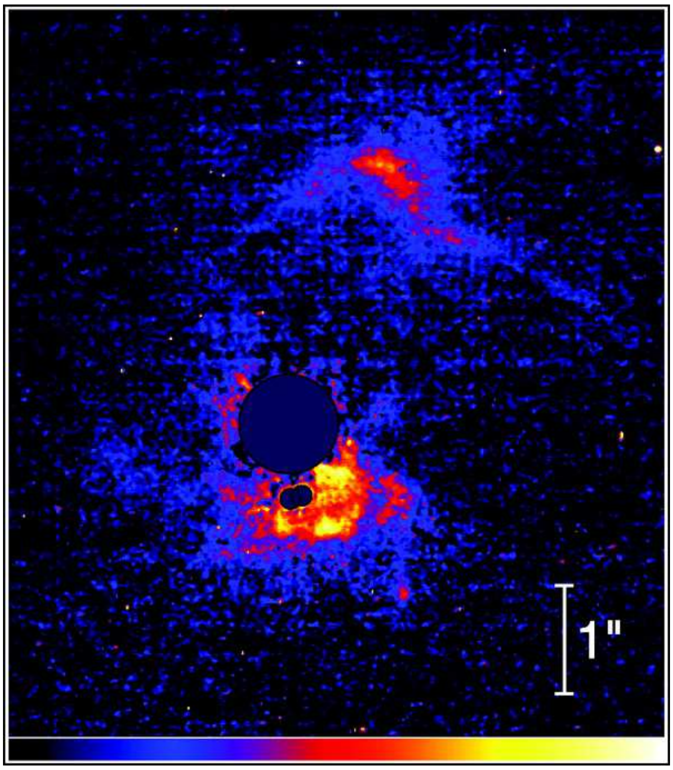

Figure 4: False-color continuum-subtracted image of the 2.12 μm quadrupole line of molecular hydrogen in T Tau. The immediate area of the stars is blanked out to avoid distracting artifacts. Note the arcs to the northwest of T Tau N and west of T Tau S. (from Herbst et al. 2007)

portunity to use T Tau N as astrometric reference and determine the absolute motion of T Tau Sa and Sb around their center of mass (Duchêne et al. 2006; Köhler et al. 2008; Köhler 2008). This way, we can get an estimate for the mass ratio of Sa and Sb. Together with the sum of their masses resulting from the orbit, we can calculate individual masses for the two stars. With the latest orbit solution by Schaefer et al. (2013), we find $M_{\rm Sa} = 2.3 \pm 0.3\,M_\odot$ and $M_{\rm Sb} = 0.4 \pm 0.2\,M_\odot$. The mass of T Tau N was estimated to be about $2\,M_\odot$, based on its spectral energy distribution (Loinard et al. 2007b). This means that T Tau Sa is the most massive star in the triple, although it is invisible in the optical.

T Tau Sb appears to be a "normal" low-mass pre-main-sequence star hidden behind a thick layer of extinction ($A_V \approx 15$ mag, Duchêne et al. 2005). T Tau Sa is more massive, but also more obscured, which makes it the prototypical IRC in the system. Reipurth (2000) suggested that T Tau N appears unobscured because it was ejected into a distant bound orbit and moved out of the dense cloud core, while T Tau Sa/Sb moved deeper into the cloud.

Outflows...

As a typical classical T Tauri star, T Tauri is surrounded by a number of nebulous patches. Hind's nebula is located about 35″ to the west. Burnham (1890) discovered a faint and diffuse nebula surrounding T Tauri with a diameter of a few arcseconds, which was later named Burnham's nebula (HH 255). T Tauri also drives the giant bipolar flow HH 355, which extends 38 arcmin in roughly north-south direction (Reipurth et al. 1997). Using high-resolution, long-slit spectra of the nebulosity around T Tauri, Böhm & Solf (1994) identified two outflow systems, one oriented southeast-northwest, and a second flow in east-west direction. Herbst et al. (2007) suggest that the east-west outflow arises from T Tau S, although they could not determine which of the two components produces it (Fig. 4).

Gustafsson et al. (2010) used high-spatial-resolution, integral-field spectroscopy to study the messy environment within 300 AU (2″) of T Tauri. By comparing their images with the data of Herbst et al. (2007), they could measure proper motion for some of the blobs. This way, they identified yet another outflow moving away from T Tau S in south-west direction. The driving source for this outflow appears to be T Tau Sb, while Gustafsson et al. argue that the southeast-northwest outflow is coming from T Tau Sa. By exclusion and because of the (lack of) proper motions, they assign the east-west outflow to T Tau N. In this picture, the east-west outflow is moving at an angle of only $\sim 20^\circ$ to the line of sight. Its location due west of T Tau S is only a coincidence.

Our confusion about the driving sources of the jets is at least partly caused by the significant motion of the stars between the time a blob is ejected into an outflow and the time we observe it. Together with the uncertainty in the motion of both the stars and the gas, it is difficult to find the proverbial smoking gun.

... and disks

Where there are outflows from young stars, there are usually also circumstellar disks. Akeson et al. (1998) observed T Tauri with the BIMA millimeter array at $\lambda = 3\,\mathrm{mm}$ and found dust emission centered at the position of T Tau N. They interpreted the emission as coming from a circumstellar disk and estimated its parameters by fitting a flat-disk model. The outer radius was estimated to be about 40 AU, smaller than the projected separation between T Tau N and S. This means that the disk around T Tau N does not cause the strong extinction in the line of sight to T Tau S. Akeson et al. did not detect emission at the position of T Tau S, which rules out a greater circumstellar mass around T Tau S.

Walter et al. (2003) mapped the environment of T Tauri with long-slit far-UV spectra. They found extended H_2 emission up to $10''$ from the stars. A dip in the brightness profile at the location of T Tau S indicates that 85% of the fluorescing gas is *behind* T Tau S. They concluded that T Tau S is not obscured by a large disk surrounding T Tau N. Rather, we might have just the opposite situation, and the strong variability of T Tau N before 1917 might have been caused by obscuration from circumstellar material around T Tau S.

Duchêne et al. (2005) studied the system with high spatial and spectral resolution in the infrared. From their IR photometry of T Tau Sb, they derive an extinction of $A_V \approx 15\,\mathrm{mag}$. They explain it with the structure seen in absorption by Walter et al. (2003), which means that it extends in front of T Tau Sa as well. This implies that it is too large to be a circum*stellar* disk, but it could be a circum*binary* envelope or disk.

In the spectra of T Tau Sa, Duchêne et al. found absorption lines of CO. Since the absorption lines are not detected in the spectrum of T Tau Sb, and since the derived gas temperature is $\sim 390\,\mathrm{K}$, the gas has to be located within a few AU of T Tau Sa. Furthermore, the column density of CO gas corresponds to an extinction of $A_V \approx 90\,\mathrm{mag}$ (assuming an interstellar-like gas-to-dust ratio, although the ratio might be very different in the circumstellar material). This explains why T Tau Sa has never been seen at optical wavelengths.

Duchêne et al. suggest that T Tau Sa has a circumstellar disk seen almost, but not exactly edge-on. The light we receive is a combination of starlight and inner disk emission. The IR spectrum shows no photospheric features, which could be explained by a spectral type between late B and mid-F, in line with the dynamical mass determination.

In an attempt to resolve the mystery around the disks in the T Tauri system, Ratzka et al. (2009) observed it with even higher spatial resolution, using the mid-infrared interferometric instrument MIDI at the VLTI. To model their data, they used a sophisticated disk model based on the radiative transfer code MC3D. The results for T Tau N confirm the earlier measurements: A circumstellar disk seen almost face-on with an outer radius of 80 AU (smaller than the projected separation between T Tau N and S). The binary T Tau S is well-resolved interferometrically, but not photometrically, which makes the interpretation of the data more difficult. To disentangle the contribution of T Tau Sa and Sb to the photometric and correlated flux, they assumed a model of T Tau Sb that describes it as a normal low-mass T Tauri star behind an absorbing screen. It is surrounded by a circumstellar disk seen almost face-on, truncated by the close neighbor T Tau Sa. With this model, the interferometric data indicate a structure elongated in north-south direction, probably a circumstellar disk seen almost edge-on. Therefore, T Tau Sa might again be seen as the driving source for an east-west outflow system.

Despite the puzzling complexity of the T Tauri system (see Fig. 5), it is clear that the disks of the three stars are misaligned with respect to each other. The jury is still out on the orbits, but there is no obvious alignment of the orbits with one of the disks either.

Still a variable star

Since 1917, the brightness of T Tauri in the optical has shown only small variations. The same is true for the infrared brightness of T Tau N since the beginning of infrared observations in the 1980s. However, T Tau S has shown large variations in the near- and mid-infrared. It is not easy to find the culprit in the Sa/Sb binary, since many of the observations did not resolve the pair, but van Boekel et al. (2010) argue that the variability is mostly caused by the IRC T Tau Sa. Variable extinction, variable accretion, or a combination of both have been proposed as reason for the variability (Ghez et al. 1991; Beck et al. 2001; Beck et al. 2004; van Boekel et al. 2010). However, van Boekel et al. observed T Tauri through a narrow-band filter at $12.81\,\mu\mathrm{m}$ and witnessed a change in the N/S brightness ratio by 26% in four days. They argue that an absorbing screen would have to move with $\sim 210\,\mathrm{km/s}$ to uncover the emitting region within four days. An object moving so fast would not stay in the system very long. Rather, van Boekel et al. suggest that at least the short-term variations are caused by variable accretion, which may have been induced by the periastron passage of T Tau Sb in 1995. Since T Tau Sb has passed its apastron in 2009, T Tau Sb should have become fainter and less variable by now. However, there is no sign of it getting fainter, although there are not enough observations to say much about its variability (van Boekel, Schaefer, priv. comm.).

The future of T Tauri

Walter et al. (2003) nicely summarized the situation: "T Tauri continues to confound and perplex, but better observational data are yielding new insights." This has continued in the last 10 years, and will probably continue in the future. Therefore, T Tauri will remain among the first targets to observe when a new telescope or instrument is commissioned. In the near future, we can hope to find out how large the disks around the stars really are and how they are oriented. We might even be able to figure out how many outflows there are and identify their sources. In the not-so-near future (but still within my lifetime, if nothing bad happens), we will witness the next periastron passage of T Tau Sb and see whether it disturbs the accretion onto T Tau Sa. Unfortunately, following the orbit of T Tau S around N will require a few hundred years, and only future generations can tell whether the strong variability of T Tauri in the optical will occur again when T Tau N and S have completed one orbit around each other.

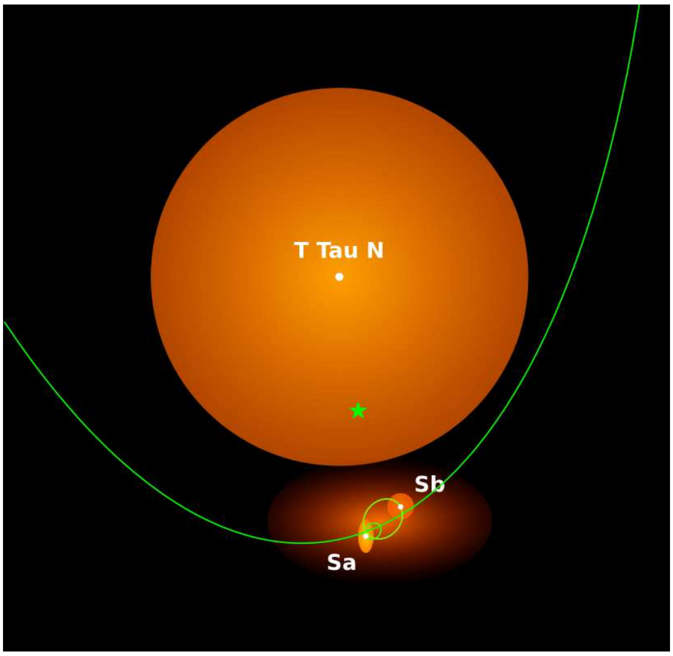

Figure 5: Sketch of our current knowledge of the disks and stars in the T Tauri system. T Tau N is surrounded by a large disk seen almost face-on. The disk around T Tau Sb is also seen almost face-on, but it is truncated by its close neighbor T Tau Sa. The disk around T Tau Sa is truncated and seen nearly edge-on, causing the large amount of extinction. Both T Tau Sa and Sb are surrounded by a circumbinary envelope or disk, which is responsible for 15 mag of visual extinction. The green lines show the orbits of T Tau Sa and Sb around their common center of mass, and their orbit around T Tau N. The latter orbit has to be regarded as uncertain, since the position angle of T Tau S has changed by only about 10° since its discovery. Finally, the green star shows the common center of mass of T Tau N, Sa, and Sb.

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