The Formation of Binary Stars
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Binary Stars: Historical Milestones

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Abstract. This is a brief historical review of the discovery of binary stars, starting in the 18th and 19th century with the work of W. Herschel, W. Struve, and their famous sons. I describe how Ch. Doppler in 1842 found the Doppler effect in connection with the colours of double stars. I also describe how the observation of the stationary Calcium H and K lines in the spectrum of the spectroscopic binary δ Ori led to the discovery of the interstellar medium by J. Hartmann in 1904 with the Potsdam refractor. Some steps in the discovery of *young* binary stars are recounted, starting with the paper of Joy and van Biesbroeck in 1944. The history of ideas regarding the origin of binary systems is also briefly reviewed, beginning with J. Michell's statistical argument in 1767 that many close visual pairs of stars must indeed form *physical* systems, and W. Herschel's definition of a binary star as "a real double star - the union of two stars that are formed together in one system, by the laws of attraction".

1. Welcome[1]

On behalf of the SOC I would like to welcome you all to our IAU Symposium 200 on "The Formation of Binary Stars". I am really pleased to see so many of you here in Potsdam. I would also like to welcome you on behalf of the IAU and particularly on behalf of IAU Commission 26 "Double and Multiple Stars" of which I am currently the President. One of my goals in this capacity was to have the first IAU Symposium on binary star formation, and indeed we made it. We even got the prestigious symposium number 200, a perfect choice for our topic. Finally I would like to welcome you on behalf of the Astrophysical Institute Potsdam and its director Günther Hasinger who already introduced you to the location and some of the historical aspects of the former Astrophysical Observatory Potsdam, associated with such famous names as Albert Michelson, Karl Schwarzschild, Ejnar Hertzsprung, and Albert Einstein.

2. Binary Stars — the Potsdam Connection

Potsdam has a long tradition in binary star studies, especially radial velocity observations of spectroscopic binaries. In fact, it was here on Telegraphenberg,

[1]This is an edited transcript of the welcome address and introductory talk.

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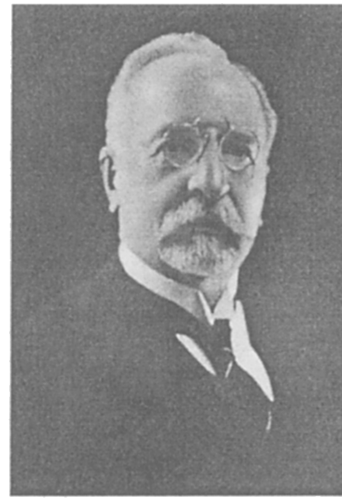
Herrmann Carl Vogel

(1841 - 1907)



Johannes Franz Hartmann

(1865 - 1936)

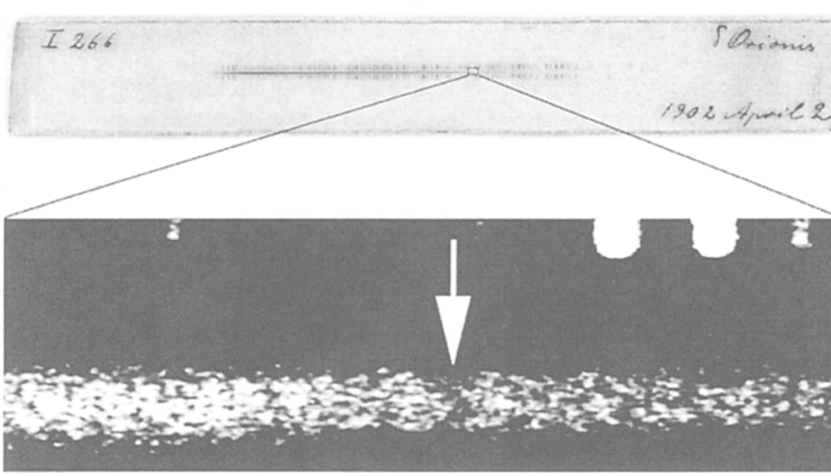


Figure 1. One of the original discovery plates of the stationary Ca K line in the radial velocity spectrogram of δ Orionis taken by Hartmann in 1902. The size of the glass plate is almost exactly to scale. The δ Ori spectrum is sandwiched between two calibration spectra, above and below, and an extraction is shown enhanced on the bottom.

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where H.C. Vogel in 1889 discovered the first single-lined spectroscopic binary (Spica), while E.C. Pickering at Harvard a few months earlier had discovered the first double-lined spectroscopic binary (Mizar). Vogel also showed observationally that Algol, the eclipsing variable found by J. Goodericke in 1782, is actually a double-lined binary system. Given these successes, Vogel managed to convince the last German Emperor, Wilhelm II, to purchase a better telescope - the 80/50 cm double refractor which is still in place today, but no longer used. We will have a chance to see this telescope tonight when we have our welcome reception in the refractor cupola.

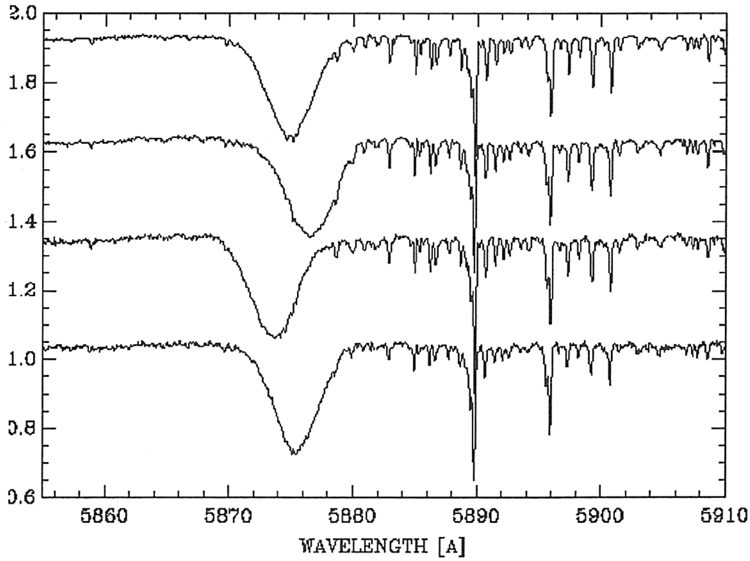

Figure 2. Radial velocity measurements of the orbital motion of the δ Ori close physical pair (SB1, P = 5.7 days) during four nights (2000 January 18, 19, 23, 24). The observations were made with the echelle spectrograph at the Tautenburg 2 m telescope in Thuringia, Germany, by E. Guenther. The spectral resolution was R = 35,000. Note the shifting of the rotationally broadened He I lines (FWHM = 215 km/s) near 5876 Å, while the Na D1 and D2 lines at 5890 and 5895 Å remain narrow and "stationary". This demonstrates the presence of neutral Na in the line of sight toward this Orion binary object. From observations similar to these, but using the stationary Ca II H and K lines at 3968 and 3933 Å, Potsdam astronomer J. Hartmann in 1904 correctly deduced the presence of an "interstellar medium" for the first time.

One of the greatest discoveries made with the Potsdam double refractor was the discovery of the interstellar medium, inferred from the stationary Ca H and K lines seen in the photographic spectrograms of the single-lined spectroscopic binary star δ Ori, which is one of the Orion belt stars. The observations were made by J. Hartmann, Vogel's assistant, in the winters of 1901/2 and 1902/3 (Hartmann 1904). Figure 1 shows both Vogel and Hartmann, as well as one of their photographic spectrograms which we found in our Potsdam plate archive at the AIP. We repeated J. Hartmann's experiment with a modern CCD spectrograph at the Tautenburg 2 m Schmidt telescope, and the result is shown in Figure 2.

The interstellar medium being the raw material from which stars form, the study of binary star formation nicely comes together in Potsdam. Incidentally, J. Hartmann is the same Hartmann whose name is intimately connected to the Hartmann test in order to measure telescopic aberrations; he invented this test because the Potsdam refractor was found to be flawed. The name appears also in the term Shack-Hartmann wavefront sensor used in adaptive optics to measure atmospheric aberrations. This technique is now widely employed to obtain high-spatial resolution diffraction-limited observations, and has recently been applied to the search for companions around young stars. The loop is closed!

3. The Discovery of Binary Stars — a Retrospective

At about the time when George Washington became the first President of the United States and when Frederick the Great was King of Prussia (1740-1787), Reverend John Michell (1767), in a paper read before the Royal Society of London, realized that many double stars which appear to consist of two stars placed close together in the sky must in fact be in close physical proximity to each other, arguing that the frequency of near stars per unit area around a given star often exceeds that expected for the observed average surface density. Michell thus has the credit of being the first to establish the existence of physical systems[2] among the visual double stars.

3.1. Classical Studies

Observational data to support Michell's deduction came later, when Sir William Herschel (Figure 3), in July 1802 (two years after he had discovered infrared radiation), presented his famous paper[3] where he coined the term "binary star" and defined it to designate "a real double star - the union of two stars that are found together in one system, by the laws of attraction". One year later, he presented an "account of a series of observations on double stars, comprehending a period of about twenty-five years which, if I am not mistaken, will go to prove that many of them are not merely double in appearance, but must be allowed to be real binary combination of two stars, intimately held together by the bonds of mutual attraction". He was not mistaken. Indeed, Castor was the first system

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[2]The formula $\log(\rho) = 2.8 - 0.2$ m gives a crude angular separation, ρ (in "), between physical and optical pairs for apparent visual magnitude m, e.g. $\rho = 10$" for m = 9 mag (Aitken 1935, p. 35)

[3]Herschel was originally interested in using close double stars of unequal brightness to measure accurate parallaxes for the brighter component assuming the fainter object is much further away, and presented the idea in 1781, the year when he also discovered Uranus. In the same year, J.E. Bode in Berlin published Ch. Mayer's "Verzeichnis aller bisher entdeckten Doppelsterne", the first ever double star catalogue comprising 80 pairs, as part of the Astronomisches Jahrbuch. Before in 1779, Mayer had published a booklet where he speculated on the possibility of small suns revolving around larger ones.

Figure 3. Sir William Herschel, the man who coined the term 'binary star' and the first astronomer to observe orbital motion.

where he showed that the change in position of the components was real and due to orbital motion. Within a year, he had analysed a set of fifty additional double stars, most of which turned out to be real binaries.

The man who made the next real advance in double star astronomy was W. Struve in Dorpat (today's Tartu in Estonia) after receiving the celebrated Fraunhofer refractor in 1824, which for the first time was equipped with an excellent driving clock and thus allowed to make precision measurements. In about two years, in only about 120 nights of actual work, he managed to survey 120,000 stars! Of these, he detected around 3000 binaries. However, Wilhelm Struve's fundamental contribution is his 1837 publication *Mensurae micrometricae* (in Latin!) with some 10,000 micrometer measurements, the Bible of 19th century double star astronomy.

Both William Herschel and Wilhelm Struve had sons who followed in their fathers' footsteps, continuing the discovery of binary stars. Sir John Herschel and Otto Struve both published monumental pieces of work on binary stars: Sir John in 1847 issued the *Results of astronomical observations made during 1834-1838 at the Cape of Good Hope*, i.e. the first catalogue of binary stars in the southern hemisphere (417 entries, for the first time ordered in Right Ascension), while Otto Struve working at the new Imperial Observatory at Pulkovo (St. Petersburg) in 1850 published what became known as the O Σ or Pulkovo close double star catalogue (408 entries).

The next major step was the discovery of the Doppler effect in 1842 by Ch. Doppler (Figure 4) from Austria, then working in Prague. Amazingly enough, this discovery was based on the colours of binary stars, as Doppler got his idea

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theorising that the different colours of binary stars (often blue and red) would arise from blue- and redshifted light of binary star components orbiting each other in opposite directions! Doppler's paper was entitled: "Ueber die farbige Natur der Doppelsterne". Although his theory was wrong in detail, it was correct in principle, and it is true that without the Doppler effect we would not know the masses of stars, the masses of galaxies, nor the Hubble constant.

We must jump forward in time, and can only mention in passing the achievements of F.W. Bessel, A. Auwers, A.G. Clark who found and analysed the variable proper motion of Sirius, and ultimately in 1861 discovered its faint, white dwarf companion, more than 10 mag fainter than the primary and at 7.5" separation. This milestone marks the beginning of astrometric binary searches.

The problem of deriving the orbital elements of a visual binary star was first solved by F. Savary and by J.F. Encke in 1827, utilizing four complete measures of angle and separation, while Sir John Herschel in 1832 added another method based solely on angle measurements. Clearly, close visual pairs were best suited for the detection of relatively fast orbital motion, and some private observers like Reverend W.R. Dawes and especially Baron E. Dembowski were very skillful in finding such systems in great numbers. They bridged the gap until around 1870, when S.W. Burnham, a clerk at the US District Court in Chicago, entered the scene and influenced it for the next 40 years. His binary data are distinguished because of their great accuracy; he was able to resolve sub-arcsec systems. His *General Catalogue of (13,665) Double Stars within 121 Degrees of the North Pole* was published in 1905. In the same year, Campell and Curtis published the *First Catalogue of Spectroscopic Binaries*, with 140 entries, based on measurements with the Mills Spectrograph at Lick Observatory. The successor to Burnham was R.G. Aitken who published a *New General Catalogue of (17,181) Double Stars* in 1932. However, he is best remembered for his classic textbook *The Binary Stars* (Aitken 1935), which includes a treasure of historical details, in part discussed here. Another influential binary star monograph did not appear until much later (Batten 1973). This brings us to the present epoch.

The first serious census of the binary frequency of Main Sequence stars was given by Heintz (1969), estimating a multiplicity of 80–85 %, while the first systematic attempt to study the frequency distribution of semi-major axes and mass ratios of binary stars with solar-type primaries was made by Abt and Levy (1976); see also Abt (1978, 1983). These authors found a uni-modal period distribution but claimed that wide binaries are randomly paired according to a van Rhijn luminosity function (equivalent to a Salpeter IMF), while the properties of close binaries are more correlated. An impartial critique of these and other studies was given by Herczeg (1984). The definitive paper on this subject was published by Duquennoy and Mayor (1991), studying the binary statistics of G-dwarf primaries within 20 pc of the Sun (164 systems). They found a binary frequency of about 60 % and confirmed the uni-modal and broad orbital period distribution with a characteristic peak period of 180 years, corresponding to a peak in the semi-major axis distribution of 30 AU for a 1 $M_{\odot}$ binary system (remember also Öpik (1925) who originally derived a f (log a) = const 'law'). The mass ratios of the wider pairs were found consistent with random pairing of the components. Furthermore, they derived an eccentricity distribution $f(e) \sim e$ for the wider pairs. Finally, they derived the important incompleteness corrections.

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Figure 4. Christian Doppler, the man who in 1842 discovered the Doppler effect, inspired by the colours of binary stars.

3.2. Studies of Young Binaries

The studies of young binaries began with Joy and van Biesbroeck (1944) who found that the young stars RW Aur, UY Aur, UX Tau, UZ Tau, and S CrA were binary systems with separations of the order of 1". Herbig (1962) added 24 more T Tauri stars to the original list of five young binaries. Cohen and Kuhi (1979) found another 34 systems.

Then Dyck et al. (1982) discovered that the prototype T Tauri star, T Tauri itself, was a binary of 0.7" separation. He made this discovery by applying a new technique, the infrared speckle technique (Labeyrie 1970). For me personally, this impressive discovery is what sparked my interest[4] in the subject. When more high spatial resolution observations came along, especially the K-band lunar occultations pioneered by Simon et al. 1987, the time had come for the first reviews of "Pre-Main Sequence Binaries" (Reipurth 1988, Zinnecker 1989). These provoked both Ch. Leinert and A. Ghez to take on the subject and start their young binary star speckle surveys. At the same time, the findings of the first survey for young *spectroscopic* binaries was published by Mathieu, Walter, & Myers (1989) who observed a binary frequency of $(9 \pm 4)\%$ for young binaries with orbital periods less than 100 days. This result is particularly interesting, because the frequency is identical to that of the solar-type field stars (Duquennoy

[4] As a consequence, I distilled my own first account on "Binary Statistics and Star Formation" (Zinnecker 1984) and started a collaboration with A. Chelli and Ch. Perrier and later with J. Christou and S. Ridgway, and finally with Ch. Leinert, to conduct infrared speckle surveys of young binaries at the ESO, Kitt Peak, and Calar Alto Observatories, respectively.

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& Mayor 1991) and also because the stars were mainly X-ray selected. The discovery of the first double-lined pre-Main Sequence stars, the X-ray selected T Tauri stars V826 in Taurus (Mundt et al. 1983) and Parenago 1540 in Orion (Marschall & Mathieu 1988), preceded the above survey.

Note that the advent of X-ray observations and the discovery of X-ray binaries rekindled the interest in binary stars in the 1970s, long before the new population of pre-Main Sequence stars, named weak-line or naked T Tauri stars, were discovered in the first X-ray surveys of star forming regions (Walter et al. 1988). Meanwhile the All-Sky X-ray survey done with ROSAT has provided complete samples of these pre-Main Sequence objects, and the frequency of visual binary systems among them is equal to that of the classical T Tauri stars (Brandner et al. 1996, Köhler & Leinert 1998).

In retrospect, Dyck et al. (1982) opened the floodgates. However, it was not until 10 years later (Nov. 1993) when, in the time span of one month, three important binary surveys were published: Reipurth & Zinnecker (red CCD survey of more than 200 southern hemisphere T Tauri stars), Leinert et al. (K-band speckle survey of about 100 T Tauri stars in Taurus to K=9.5), Ghez et al. (K-band speckle survey of about 70 T Tauri stars in Taurus and Ophiuchus to K=8.5). These surveys were all first presented at the 1992 Atlanta IAU Colloquium No. 135. The subject was all nicely summarised and synthesised in the Annual Reviews Article on "Pre-main Sequence Binaries" by the co-chair of this Symposium (Mathieu 1994). One of the focal points was that the extrapolated binary frequency of T Tauri stars in the Taurus-Auriga T association was a factor of two higher than the binary frequency of solar-type field stars, a result that we are still trying to digest today.

4. Binary Star Formation — a Brief History of Ideas

The first theory of binary star formation was the capture theory proposed by G.J. Stoney (1867). As the name implies, it was thought that two stars, originally independent, might approach each other under such conditions that each would be forced to revolve with the other about a common center of gravity. This theory in its original form has been completely abandoned as too unlikely. A modern version of this theory is the tidal capture theory, applicable to dense star clusters such as globular clusters (Fabian, Pringle, & Rees 1975) or the theory of gas drag in colliding protostars with extended disks or envelopes (Silk 1978). In fact, these processes may be at work in the core of young clusters to explain the high frequency of tight binaries among massive stars (Mermilliod & Garcia, these proceedings).

Another long-standing theory involves the fission mechanism. This theory describes the behaviour of a rotating, homogeneous, incompressible fluid mass, as a sequence of equilibria under gravitational contraction. It all started with a debate between Newton and Cassini, whether the rotating earth was an oblate or a prolate body (F. Shu, priv. communication). It was P.-L. Maupertuis leading an expedition to Lapland in 1736 who gave an observational answer, in favour of Newton (oblate) and against Cassini (prolate).

MacLaurin, around 1740, had a general formula to describe axisymmetric spheroidal equilibria and flattening of a rotating gravitating fluid. However, it was only about a hundred years later when Jacobi in 1834 discovered the sequence of non-axisymmetric ellipsoidal figures of equilibria (so-called tri-axial Jacobi ellipsoids). With increasing rotation (angular momentum) these equilibria become egg-shaped and can bifurcate into two objects (see the textbook by Tassoul 1978, Chapter 11). This led Jeans (1918) to make his famous conjecture that "fission" is the formation process of close binaries, while he favored another process usually called "condensation of separate nuclei" as the process by which wide binaries form, the dividing line lying at a period of 55 days, according to Jeans. The separate nuclei theory was first advanced by Laplace in 1796, while fission and subsequent separation was discussed by Lord Kelvin and P.G. Tait in 1883. Apart from Jeans, Henry Norris Russell (1910) had earlier supported the fission origin of hierarchical triple/quadruple systems (two bifurcations).

In practice, fission does not seem to work. This became apparent when considering centrally condensed, differentially rotating fluid bodies (differentially rotating polytropes), which resemble stars much better than objects with uniform, solid body rotation. When the ratio of rotational to gravitational energy exceeds a critical value ($\beta_{crit} = 0.27$), the rotating fluid goes bar-unstable on a dynamical timescale (Bodenheimer & Ostriker 1973), and ejects spiral arms that transport angular momentum outwards, thus preventing fission from occurring. However, the last word on fission as an instability in a contracting quasi-hydrostatic star has yet to be spoken (cf. Tohline & Durisen, these proceedings).

While fission implies a sequence of equilibria with small changes due to dissipation (secular instability, operating for $\beta = 0.14$–0.27), fragmentation is a dynamic process in a collapsing cloud. Originally introduced by Hoyle (1953) and Hunter (1962) in qualitative and analytic terms, the modern theory of cloud fragmentation was made possible by numerical simulations (e.g. Larson 1978). Several papers during this Symposium will address various aspects of the fragmentation process. Hierarchical fragmentation during rotational collapse has been invoked to produce binaries and multiple systems and explain many of their observed properties (e.g. Boss 1988), although fully 3D calculations including magnetic fields are still missing. The role of magnetic fields in fragmentation (inhibiting or promoting) has yet to be clarified, but indications are that magnetic fields help (Boss, these proceedings). In any case, they can help to solve most of the angular momentum problem by magnetic braking (Ebert 1960, Mestel 1965, Mouschovias 1977).

Specific versions of fragmentation are disk fragmentation and filament fragmentation. Bonnell (1994) concludes that fragmentation of a rotating disk around an incipient central protostar is possible, as long as there is continuing infall. Zinnecker (1989) pointed out that tumbling filaments, rotating end over end, would tend to fragment into binaries with high eccentricity, a conjecture borne out by numerical simulations (Bonnell & Bastien 1992). Whitworth and his students (Turner et al. 1995, Whitworth et al. 1995) follow numerically the outcome of impulsively triggered fragmentation, a suggestion originally made by Pringle (1989) who dubbed the process "prompt initial fragmentation". The combination of fragmentation and subsequent accretion from the envelope may help to explain the mass ratios and circumstellar disk properties of binary stars (Bate, these proceedings). To complete the history of ideas, the theory of the "disintegration of small star clusters" must be highlighted. It may naturally

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account for the high frequency of binary and multiple stars as the stable decay products of unstable small N-body configurations. Its beginning goes back to a seminal paper by van Albada (1968); see also Harrington (1975) and Szebehely (1977). This theory is now gaining more and more support, after realizing that the chaotic nature of the gravitational interactions of young stars with disks would give rise to a large dispersion of binary properties such as a very wide distribution of semi-major axes and a very hierarchical structure of multiple systems[5], as observed. An excellent critical review on binary star formation theories is Pringle (1991) who also points out the need to study Population II binary statistics (Pringle 1989).

5. Binary Stars — Past, Present, and Future

In this introductory paper, I have tried to outline some facets of the past astronomical history in our field. Such an effort must necessarily be subjective and incomplete. I hope it'll prove useful nonetheless. For the most recent developments, I refer you to my triannual report on young binaries in the Transactions of the IAU, Vol. XXIV A (Zinnecker 2000). The future is bright, as this Symposium will show. I am particularly thrilled by the advent of optical and infrared long-baseline interferometry (VLTI, the Keck I/II interferometer, and later LBT), and the prospects of resolving pre-Main Sequence spectroscopic binaries, preferably double-lined ones. This will allow us to determine a sufficient number of short period orbits and even orbital parallaxes. Therefore, we will not only get dynamical masses of the individual components, but – through multi-wavelength observations – we will also be able to obtain resolved component luminosities and colour indices. All these data are required if we ever are to calibrate theoretical pre-Main Sequence evolutionary tracks. The next boost can be expected when ALMA, the mm/submm long-baseline interferometer, will be in place. Then around 2010 we will finally be in a position to probe the formation of binary stars by direct protostellar mm/submm imaging and spectroscopy.

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[5] I refer to the papers both by Clarke and by Larson in these proceedings, who elaborate on this picture, taking into account dissipative interactions of young stellar objects with protostellar disks as well as gas drag effects which can cause orbital migration.

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Eike Guenther (left) explains the Potsdam double refractor to his friends.

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