Star-Disk Interaction in Young Stars
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Summary and concluding remarks

Immo Appenzeller

University of Heidelberg, Landessternwarte, Königstuhl, D 69117 Heidelberg, Germany
email: I.Appenzeller@lsw.uni-heidelberg.de

Abstract. This symposium was characterized by an intense exchange of new information and by lively discussions on many aspects of the formation and early evolution of low-mass stars. The observational data presented at this meeting, obtained in spectral regions ranging from X-rays to submm waves, were found to be remarkably consistent with the current magnetospheric disc-accretion paradigm for young stellar objects. But there remain open questions, and a full understanding of the star-formation process will require much additional work.

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Agreeing to present a meeting summary comes with the obligation to listen carefully to all the talks and to study all the posters. This is not always an easy or pleasant task. At this conference listening to all the presentations was a real pleasure. Among the many conferences which I attended, this IAU symposium definitely was one of the highlights and one the most rewarding events.

As indicated by the title of the symposium, the central topic of this meeting has been the interaction of very young stars with their accretion disks. The conference was dedicated to Claude Bertout who provided decisive ideas and important details to this subject. From the table of contents of these proceedings it is evident that the themes actually discussed at this meeting went well beyond the central topic and included many different aspects of low-mass star formation. Among these themes were basic concepts of the star-formation process, questions related to the formation and evolution of planetary systems, and new results on young stars of intermediate mass and of very low mass. In addition to to highly informative invited and contributed talks we enjoyed many attractive and well organized posters.

Compared to earlier star formation conferences there was a surprising amount of consensus and agreement on many of the questions which were disputed in the past. This seems to indicate that some basic facts are by now understood and well established. These issues, which, according to the results presented here, appear to be firmly established will be summarized the first section of this report. In a second part of my summary I will list the open questions, the gaps in our present understanding, and potential ways to achieve further progress.

1. What we (seem to) know

1.1. *The observational evidence*

IAUS 243 started with two excellent reviews of the current magnetospheric disk-accretion paradigm of young low-mass stars. First Claude Bertout described the basic model and its interesting history. Then Gibor Basri discussed the spectroscopic evidence which led to our present concepts. Most of the following talks reported new observational results, new models, or new numerical simulations concerning details of the disk-accretion scenario. Remarkably, practically all the new data supported or confirmed the current paradigm.

The magnetospheric disk-accretion model was initially developed on the basis of optical line profiles and NIR photometry. As shown by Tim Harries and his co-workers, improved radiative transfer models result in even better agreement between the computed and the observed Balmer line profiles. On the other hand, it has been known since a long time, that the Balmer line profiles can be ambiguous and that such agreements do not necessarily prove that the models are correct. Therefore, it will be important to extend the new profile calculations to lines which are formed in well defined regions of the accretion-flow, disk, and wind systems. An example of such lines is He I 10830, for which Suzan Edwards showed us very interesting new results. Originating from a high, metastable state of He I, this line is formed in a low-density high-excitation environment. Also particularly valuable in this context are the observations of the UV "transition region" lines, formed in the accretion-shock cooling zones (see David Ardila's contribution), and the profiles of the IR lines of CO, formed in the cool inner disks (described by John Carr).

Among the highlights of this meeting was new and detailed data on the X-ray emission from young stars of different mass. Although there may still be uncertainties concerning the exact location of the X-ray emitting regions, the talks by Thierry Montmerle and Manuel Guedel showed that the observed X-ray properties of T Tauri stars are well explained by the current models. From the present data it seems that the accretion shocks as well as hot magnetospheric coronae, and possibly shocks in the inner jets contribute the observed X-ray flux.

As pointed out by several authors, and as demonstrated with convincing examples by Silvia Alencar, time variability observations provide particularly good tests of model details. Obviously more such observations will be highly valuable and well worth the significant amount of observing time which is needed for such work.

From the talks by Jerome Bouvier and by Jochen Eislöffel we learned that there is at least basic agreement between the statistics of the observed rotational velocities of young stars and the model predictions. The fact that some stars seem not to follow the expectations has to be investigated with a closer look at the corresponding stellar samples.

In spite of the impressive progress in modeling jets and outflows from young stars, there remain open questions concerning the jet physics (see § 2). But, as discussed in the talks of Sylvie Cabrit and Sean Matt (and from other contributions) it is clear that the observed outflows cannot be consistently explained without the presence and the action of large-scale magnetic fields. Thus, although the acceleration of the observed outflows may not yet be fully understood, their properties can be explained *only* in the context of the magnetospheric accretion models.

All the observational results mentioned above support or are consistent with the current disk-accretion models. No observation reported at this meeting appeared to be in serious contradiction with this paradigm.

1.2. *Magnetic fields*

At one point during the discussions Frank Shu happily noted that at this symposium magnetic fields – in the past often regarded as an unwelcome complication of star formation – was one of the major topics. Obviously, magnetic fields are an indispensable ingredient of the current models. When the scenario of the magnetospheric disk accretion was developed, the observational techniques were far from being able to measure the fields predicted by the theory. For many years these fields remained an unproven theoretical prediction. As described in Johns-Krull's excellent review, this situation has changed dramatically. Not only do we observe the fields, but important details could be established.

Most of the magnetic field measurements available at present are based on the profiles of low-excitation absorption lines originating in the cool photosphere of the observed T Tauri stars. In these lines we see fairly strong small-scale fields, which in CTTSs may cover a significant fraction of the stellar surface. No or only a small contribution of a dipole or ordered field is seen in the lines formed in the cool photospheres. However, as reported by Christopher Johns-Krull, at least in some CTTSs, a weaker, ordered large-scale field is observed in the profiles of the He I 5876 emission line, which is thought to be formed in the cooling zones of the magnetic accretion shocks. These results are in good agreement with at least part of the present magnetic disk-accretion models. Obviously, magnetic field measurements in lines produced in the accretion flow provide a particularly valuable test for these models. Therefore, more field measurements based on such lines will be particularly important for a comparison with the theory.

1.3. *Accretion flow models*

Among the most impressive results presented at this meeting were the 2-D and 3-D MHD simulations of the star-disk interaction shown by Marina Romanova and Akshay Kulkarni. Although these calculations still have to assume various physical simplifications, the computed models contain a surprising amount of detail and provide data on the structure as well as on the time evolution of the magnetospheres and accretion flows. The results of these simulations are in surprisingly good agreement with predictions made from the initial, much more simplified magnetospheric accretion models. They again seem to confirm that the basic picture is correct.

2. Open questions and future work

There seems to be general agreement that the accretion flows of young stellar objects are controlled by the common magnetosphere of the disk and the central star. However, the exact topology of these magnetospheres is far from clear. Closely related to the topology of the magnetosphere is the question of whether we always (or only sometimes, or perhaps never) have "disk-locking", and the question where the winds and the outflows from CTTSs originate. In spite of the extensive discussions of this issue, no clear answer could be given at this meeting. On the other hand, the interrelation of these questions became clearer. Progress on this question should become possible from profile observations of lines originating in the inner regions of the outflows. Such observational data will eventually allow us to decide between the different magnetospheric models.

Another question which remained open at this meeting is the origin of the observed X-rays. It seems plausible that much of the hard X-ray flux is produced in hot magnetospheric coronae. But, as discussed (e.g.) by Manuel Guedel, the origin of the soft component is less clear. This components seems to be produced in shocks. The accretion shocks of CTTSs, in principle, provide a natural explanation for this component. However, shocks are also associated with the observed jets and the current models and data do not yet lead to firm conclusions.

Detailed and extensive new MHD simulations presented to us by Christian Fendt, Jonathan Ferreira, Tom Ray and others demonstrated and confirmed that accretion disks and their magnetospheres can naturally produce collimated outflows with properties similar to those of the observed jets from young stars. A problem here is, that similar jet properties can be produced with rather different assumptions. And, although much has been learned about the physical structure of the jets, more information on the jet acceleration regions are needed to distinguish between the different models. Moreover, although the jet models usually start with dipole-like fields of the central objects, the jet evolution

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leads to quite different topologies. It will be important to develop magnetospheric models which simultaneously describe the development of a collimated outflows and the central fields responsible for the magnetic accretion from the disk to the central star.

At this meeting we saw beautiful examples of computed star-disk systems and their evolution with time. However, at present all such simulations start from some assumed initial conditions. In the real world these initial conditions are the result of the fragmentation and internal interactions in collapsing turbulent interstellar gas clouds. An important task for the future will be to clarify the correct initial conditions by modeling the formation of star-disk systems and their magnetospheres from 3-D collapse calculations, starting with the collapse of molecular clouds, or perhaps even with the formation of these clouds. A step in this direction are the models presented by Frank Shu and by Shu-Ichiro Inutsuka, which start with a rotationally symmetric magnetized cloud core. True 3-D evolutionary computations of turbulent magnetic clouds have been initiated by various groups (e.g., Heitsch *et al.* 2006, Jappsen *et al.* 2005), and present and future computers and modern numerical methods should make it possible to achieve progress in this field in the near future.

During the past years new large optical interferometers have made it possible to directly resolve the inner regions of accretion disks and mass flows around young stars. Examples of such observations have been shown at this meting by Fabien Malbet, Stefan Kraus and Tom Ray. This data provides valuable new information. However, in most cases, little more than visibilities (as a function of wavelength) or aspect ratios have been reported. Obviously, such data arouse our appetite for more detailed information. Modern NIR and MIR interferometers have the potential of producing much more detailed data and – eventually – true images. Thus, there is hope that at future meeting on this topic we will see interferometric images of the star-disk systems which are as detailed and as well resolved as the theoretical models which we have been shown at this symposium.

3. Some historical remarks

Claude Bertout ended his introductory review of this conference with a quotation from George Herbig's summary of the observational part of the IAU Symposium No. 75 ("Star Formation"), which took place in 1976 in Geneva. In his final words George Herbig predicted that "with the perspective of the years, all that we do today will certainly be seen to have been either wrong, or irrelevant , or obvious" (Herbig 1977). By now, more than 30 years later, it seems appropriate to ask, whether this prediction has become true. Although I dislike to disagree with our distinguished colleague George Herbig, according to my assessment, he was only partially correct.

Reading the proceedings of the 1976 IAU symposium, one indeed finds statements and ideas which turned out to be completely wrong or irrelevant. However, in my opinion, none of the issues discussed in 1976 appear (as seen from today) obvious. In view of the complexity of star formation, the details of this process probably will never appear obvious. And some of the information presented at the Geneva meeting was quite correct and was important for the development of our present theories.

At the time of the 1976 meeting Merle Walker's 1972 paper (Walker 1972), suggesting the presence of accretion discs in (part of) the CTTSs, was already well known, and accretion models (and new evidence supporting them) were discussed at the 1976 symposium. But, the chromospheric models of the T Tauri emission spectra were clearly more popular at that time, in part since chromospheric emission was better understood than the complex physics of accretion. Only about three years later, at the 1979 UC

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Santa Cruz Astrophysics Summer Workshop, accretion models became to be regarded as a viable alternative.

The recollection of the discussions at the Geneva symposium obviously raises the question of how much of the results of the present symposium will survive the next 30 years.

A look into the old papers shows that much of the less relevant discussions of the 1976 symposium can be traced to the incomplete and often poor observational data available at that time. In 1976 observations of very young stars were restricted to the optical wavelength range and high-resolution spectroscopy existed only for the exceptionally bright objects. Today we have much better and much more comprehensive observational data, which provide more and significantly more reliable constraints. Therefore, I suspect that there is a good chance that somebody who reads the proceedings of IAU Symposium 243 in 30 years will find that the basic features of the magnetospheric disk-accretion model of young stellar objects has been basically correct.

Finally...

Among the participants of this symposium there seems to be a strong consensus that this has been a particularly successful and pleasant meeting. This would not have been possible without the efforts of Jerome Bouvier and the very efficient LOC of this conference. Therefore, I would like to end with a big "MERCY BEAUCOUP" to Jerome Bouvier and to the members of the Grenoble LOC. You did a brilliant job and you were great hosts of a memorable event!

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