Project A2:

New constraints on disk-dissipation processes from the relation between accretion and X-ray activity

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Requested positions: 1 PhD student

Abstract:
As discussed in the general introduction, Type I transition disks (TDs), which present small inner cavities and a depleted accretion signature, are thought to be objects caught in the act of dispersal. Photoevaporation from X-ray radiation from the central star is thought to be the main driver in the dispersal of disks around solar and later-type stars.

We want to test models of X-ray driven disk photoevaporation leading to the formation of transition disks by using new observational data to study the relation between accretion rates of young stars and their X-ray emission. The aim is to combine the numerous available high-quality X-ray data of young stars in different regions with new and highly reliable accretion rates that can be derived from the new spectroscopic data on these stars. In this way, we will be able to study the relation between X-ray emission and accretion with much larger samples (hundreds of stars rather than just a few dozen) and for different regions spanning a range of ages, and to test the predictions of theoretical models of X-ray driven disk photoevaporation and the corresponding effects on the disk accretion rate. This is of fundamental importance to understand the formation and residual accretion rate distribution of transition disks.

1. State of the art and preliminary work

a) Scientific Context: the evolution of circumstellar accretion disks

In this project we want to study the connection between the X-ray radiation of young stellar objects and the properties and temporal evolution of their accretion disks. In order to define the scientific context, we start here with a very brief description of the evolution of young stellar objects (YSOs), which proceeds through a sequence of stages with different characteristics. In order to keep the text concise, it is written with a minimal amount of references; for a much more comprehensive and detailed description and references to the literature we refer to the monograph of Hartmann (2008) and the recent reviews of Alexander et al. (2014) and Hartmann et al. (2016).

When a cloud core collapses, angular momentum conservation naturally leads to the formation of a circumstellar accretion disk around the protostar. After a few 100 000 years, most of the material in the original envelope around the YSO has either collapsed onto this disk or was blown away by the outflows typically driven from protostars. The photosphere of the YSO becomes directly visible at infrared and optical wavelengths for the first time, and the YSO enters the *"T Tauri star"* (TTS) phase. The photospheric emission allows to determine the luminosity and effective temperature of the TTS. The spectral energy distribution of TTS shows an infrared excess that is caused by the warm dust in

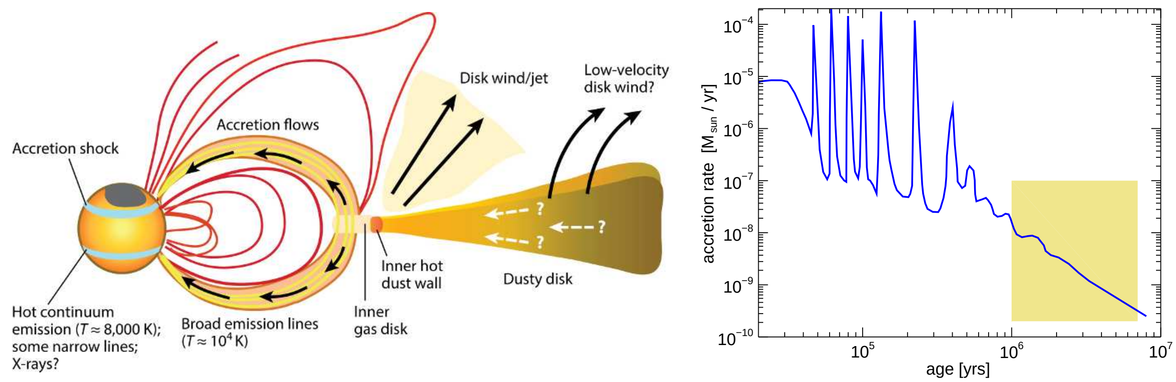

Figure 1: **Left:** Reproduction of Fig. 1 from Hartmann et al. (2016), illustrating the main features of disk accretion in YSOs. **Right:** Schematic illustration of the temporal evolution of the accretion rate (adapted from Hartmann 2008). The light-brown shaded area marks the age range we address in this project.

the disk and allows to estimate the masses of the circumstellar disks, typically a few percent of the stellar mass.

Objects in the evolutionary phase of *"classical T Tauri stars"* (CTTS) are observationally characterized by strong optical emission lines ($W(\mathrm{H}\alpha) \geq 10\,\text{Å}$), which are caused by accretion of circumstellar material onto the young star. Typical accretion rates in the CTTS phase are of order $\dot{\mathrm{M}} \sim 10^{-8}\,\mathrm{M}_{\odot}/\mathrm{yr}$. The accretion of matter from the circumstellar disk onto the central star is thought to be magnetically controlled. Stellar magnetic field lines connect the stellar surface to the surrounding disk (see illustration in Fig. 1) and lead to a truncation of the disk at or near the co-rotation radius, i.e. the radius where the Keplerian angular velocity of the disk matches the stellar angular velocity, typically a few stellar radii. The magnetic field lines connecting the disk to the star produce a complex 3D system of "accretion funnels" that channel the accretion flow to the stellar surface. The gas in the accretion funnels reaches free-fall velocities of several 100 km s^{-1} and finally generates shocks at the (proto-)stellar surface. This hot shocked gas produces the UV and optical excess emission and the strong optical emission lines of CTTS.

During the following few Myrs, the disk mass decreases, as some part of the circumstellar matter is accreted onto the star and another fraction is removed by a disk wind. As a consequence, the accretion rate also drops and the spectroscopic signatures of disk accretion get weaker; the object evolves into a so-called *"weak-line T Tauri star"* (WTTS). During this evolution, the structure of the accretion disk also changes. Observational evidence shows that many of these older disks seem to evolve an inner hole in the disk, i.e. the dust in the inner few AUs of the circumstellar environment is somehow cleared (e.g., Alexander et al. 2014; Koepferl et al. 2013). This typically happens at an age of roughly 2 ... 5 Myr, and the result is a so-called *"transition disk"* (TD) (see Owen 2016).

In the subsequent evolution, the remaining material in the outer disk is dispersed by a strong disk wind. This final disk dispersal process is very rapid ($\sim 10^5$ years) and proceeds from inside-out (Ercolano 2014). As described below in more detail, the irradiation with ionizing radiation from the central star seems to be the most important driving mechanism for this disk wind.

In the course of this evolution, the accretion rate generally decreases with time. During the very young, protostellar stages, the accretion process shows strong variability on a wide range of timescales, including rare (see Hillenbrand & Findeisen 2015), but very strong bursts of very rapid accretion (FU Ori bursts), during which the accretion rates can be enhanced by one or more orders of magnitudes for timescales from months to decades (see Hartmann et al. 2016, and the illustration in Fig. 1). With increasing age (and correspondingly lower average accretion rates), however, the frequency as well as the amplitude of the accretion rate bursts is strongly decreasing, and at ages of ≥ 1 Myr (i.e. in the

TTS stage) the accretion variability is typically less than a factor $\sim 2-3$ (see Venuti et al. 2014).

Although this description is mainly based on theoretical arguments and numerical simulations (Ercolano et al. 2011; Alexander et al. 2014), it is well supported and confirmed by an increasing body of new observational data that were collected during the last several years. In particular, numerous observations have clearly established that the fraction of YSO with optically thick disks decreases very quickly with age. The inferred (e-folding) lifetime of these disks is only about 2–3 Myr, and the fraction of disks in clusters with ages of > 5 Myr is very low (e.g., Hernández et al. 2007). This yields a clearly established upper limit to the lifetime of protoplanetary disks of less than 10 Myr, which provides a very important constraint for theories of planet formation (especially the formation of gas-giants).

While the general picture of the accretion process on YSOs is now quite well established, several observational facets of the accretion and disk evolution processes are still not well understood. One of these open questions concerns the explanation of the rather wide distribution of individual disk lifetimes around the median lifetime of about 2.5 Myr. The observational data show that some 15% of the stars disperse their disks very quickly, within just about 1 Myr. On the other hand, a similar fraction of stars manage to keep their disks even at ages of more than $5-6$ Myr. The exact reason for this considerable differences in disk lifetimes is not yet well known. This is important as the lifetime of a disk determines the timescale over which (giant) planet formation must occur. Hence the success of a given system in producing a planetary system containing gas giants strongly depends on this.

A second important question concerns the explanation of the observed wide range of individual stellar accretion rates. Observations of young clusters, where all the stars have a very similar age, indicate that for any given stellar mass, the accretion rates show a scatter of at least two orders of magnitude (see, e.g., Fig. 16 of Venuti et al. 2014). The reason why stars with the same age and mass display such a wide range of accretion rates is also not yet clear and may be related to the disc dispersal process (Owen, Ercolano & Clarke 2011; Ercolano 2014).

An aspect of fundamental importance in this context is that the disk is not just a passive “road” for the accreted material, but there is a close interconnection and interaction between the TTS and its disk. The properties of the disk determine the global accretion rate (e.g., via the viscosity) as well as the details of how the disk material is finally deposited onto the stellar surface. This determines not only how fast the star can gain mass via accretion, but also influences the temporal evolution of the internal stellar structure (and thus influences the luminosity of the protostar) as well as the evolution of its rotation rate (which is important for magnetic dynamo activity). Recent studies also suggest that the early accretion history impacts the stellar properties even after several Myr, i.e. long after the accretion process has ceased (see Baraffe et al. 2016).

On the other hand, the luminosity of the central star (which results partly from the release of gravitational energy in the accretion shock at the stellar surface) determines the irradiation of the disk, which is a major heating source for the disk and strongly influences its temperature structure. This also affects the accretion rate in the disk, which depends strongly on the temperature and the microphysical properties on the disk (e.g., via the viscosity).

As will be described below in more detail, recent results clearly suggest that the high-energy radiation of the young star, and in particular the X-ray emission, plays a very central role in the evolution and final dispersal of the circumstellar disk (Ercolano et al. 2008a,b, 2009; Owen et al. 2010; Owen, Ercolano & Clarke 2011; Owen et al. 2012).

This intricate interconnection and interaction between the evolution of the star (mass growth rate, rotational evolution, magnetic dynamo activity, level of high-energy radiation) and the evolution of the disk (time dependence of the accretion rate and the disk mass-loss rate) constitutes several feedback loops and is thus of fundamental importance for the understanding of the evolution of YSOs.

In recent years, circumstellar disks evolved into an extremely prominent research topic because they are the sites where planets form. The properties of the disk around TTS determine the conditions under which the planets form and the observational upper limit on the disk lifetime places very severe constraints for planet formation theories. This highlights the fact that **a good understanding of the properties and the evolution of circumstellar disks is also highly relevant for our theories about planet formation and early evolution.**

Since the above mentioned (mostly theoretical and numerical) studies of the star-disk interaction suggest that stellar X-ray emission is of enormous importance for the structure and the evolution of disks, it also has far-reaching consequences for the planet formation process (Ercolano & Rosotti 2015; Rosotti et al. 2013, 2015). It is therefore very important to test these models for disk evolution and disk dispersal against observations. For this, a solid understanding of the X-ray emission properties from YSOs is a basic requirement.

b) X-ray emission from YSOs

Numerous X-ray observations obtained during the last decades have clearly established that YSOs in all evolutionary stages from protostars to ZAMS stars show highly elevated levels of X-ray activity (Feigelson & Montmerle 1999; Preibisch, Zinnecker, & Herbig 1996; Preibisch & Zinnecker 2002; Preibisch et al. 2005, 2011, 2014). Typical X-ray luminosities of $\sim$ solar mass YSOs are about 10^{30} erg/s, i.e. are up to $\sim 10^4$ times higher than seen in our current Sun. The temperatures of the X-ray emitting plasma on young stars are typically 10 to 20 MK, i.e. about ten times higher than in the solar corona. The X-ray emission of the young stars is therefore considerably harder than the solar X-ray spectrum, and contains substantial fluxes in the energy range above 3 keV.

Although the relations between the X-ray activity of young stars and their stellar / circumstellar parameters were investigated in many star forming regions, nearly all of these studies suffered from limited sensitivities and corresponding incomplete X-ray detections. These problems were finally solved with the *Chandra* Orion Ultradeep Project (COUP), a uniquely deep (10-day long) observation of the Orion Nebula Cluster (ONC) with *Chandra*/ACIS (for details of the observation and data analysis see Getman et al. 2005). It is still the deepest and longest X-ray observation ever made of a young stellar cluster and produced the most comprehensive dataset ever acquired on the X-ray emission of young stars (Preibisch et al. 2005). Nearly all of the 1616 detected X-ray sources could be unambiguously identified with optical or near-infrared counterparts. With a detection limit of $L_{\mathrm{X,min}} \sim 10^{27.3}$ erg/sec for lightly absorbed sources, X-ray emission from more than 97% of the $\sim$ 600 optically visible and well characterized late-type (spectral types F to M) cluster stars was detected (Preibisch et al. 2005). Since the COUP TTS sample is *complete*, the COUP data do not suffer from the selection effects that plague the less sensitive X-ray studies of other young clusters, where a considerable fraction of the lowest mass stars remained undetected.

Two results of fundamental importance for the proposed project derived from the COUP data are, that

1. X-ray luminosity scales to stellar mass as $L_{\mathrm{X}} \propto M^{1.4}$ (Preibisch et al. 2005), and
2. the X-ray luminosity of TTS is approximately constant for $\geq$ 10 Myr (Preibisch & Feigelson 2005) i.e., during the full period of time for which disks usually exist.

The COUP data also confirmed that the strong X-ray emission from YSOs is predominantly originating from a hot, magnetically confined plasma in the stellar corona, which is the result of magnetic dynamo activity (Preibisch et al. 2005). The high X-ray activity levels are thus thought to be ultimately a consequence of the very fast rotation of the young stars (e.g., Alexander & Preibisch 2012).

Theoretical arguments suggest that the strong X-ray emission of young stars has far-reaching implications for the physical structure and processes in their circumstellar environment (e.g., Glassgold et al. 2005; Wolk et al. 2005; Ercolano & Glassgold 2013), the evolution of the disk (e.g., Ercolano 2014), the formation of planetary systems (e.g. Ercolano & Rosotti 2015), and the evolution of the atmospheres of young planets (e.g., Johnstone et al. 2015). However, detailed observational diagnostics for these suggested influences have been hard to come by, so far. One of these topics is the question we want to address in this project: How does the X-ray emission affect the evolution of the protoplanetary accretion disks?

c) Previous observational results on the relation between X-ray emission and accretion disks

About 15 years ago, X-ray observations of young stellar clusters provided the first indications that the X-ray luminosities of young stars seem to depend on the presence and the properties of accretion disks (e.g. Stelzer & Neuhäuser 2001). However, no strong conclusions could initially be drawn due to problems related to small sample sizes, incompleteness of the X-ray detected samples, and ambiguities about the disk properties. A fundamental clarification of the tentative relations between X-ray emission and the properties of accretion disks was finally provided by the COUP data. COUP showed unambiguously and in a statistically significant way that **the absolute as well as the fractional X-ray luminosities of accreting young stars are systematically *lower* by a factor of $\sim 2-3$ than the corresponding values for non-accreting stars.**

In order to find possible explanations for this surprising result, a more detailed analysis of the relation between X-ray emission and disk accretion is required. The best data on accretion rates and accretion luminosities available at the time of the COUP project were those from the study of Robberto et al. (2004), who had determined accretion rates and accretion luminosities for 30 young stars in the Trapezium cluster from Hubble Space Telescope *U*- and *B*-band photometry. The COUP data showed a weak anti-correlation of the fractional X-ray luminosity with accretion rate (and also with accretion luminosity). However, the statistical significance of this result was low, because the number of stars for which estimates of the accretion rate were available at that time was too small. Nevertheless, these results were supported by similar findings from a deep X-ray survey of the Taurus star forming region, which also showed that the X-ray activity of accreting young stars appears to be somehow suppressed (Briggs et al. 2007).

Several possible explanations for this anti-correlation between X-ray activity and mass accretion rate were suggested. One model assumed that changes in the coronal magnetic field structure by the accretion process could lead to lower X-ray emission (Romanova et al. 2004). This idea was based on the fact that the pressure of the accreting material may distort the large-scale stellar magnetic field and the magnetospheric transfer of material to the star can give rise to instabilities of the magnetic fields around the inner disk edge. The presence of accreting material should also lead to higher densities in (parts of) the magnetosphere; these high densities could inhibit magnetic heating of the accreting material to X-ray emitting temperatures.

Another suggestion was that the accreting material would cool the corona when it penetrates into active regions and mixes with hot plasma. If the plasma would be cooled below a few MK, its very soft X-ray emission would be essentially undetectable for the CCD X-ray detectors of *Chandra* and XMM-Newton, and thus the observed X-ray luminosity of the accreting stars would be lower than that of non-accretors (see also Telleschi et al. 2007).

Yet another theory suggested that the stripping of the coronal magnetic field by the interaction with the disk might reduce the coronal volume and thus the X-ray emission (Jardine et al. 2006). In stars without a circumstellar disk, the coronae extend outwards to the radius where the pressure of the hot coronal gas overcomes the magnetic field, explaining the observed increase in the X-ray emission measure with increasing stellar mass. In stars that are surrounded by a circumstellar accretion disk, the outer parts of the coronal magnetic field could be stripped by the interaction with the disk, and this might explain the observed lower X-ray luminosities of accreting stars.

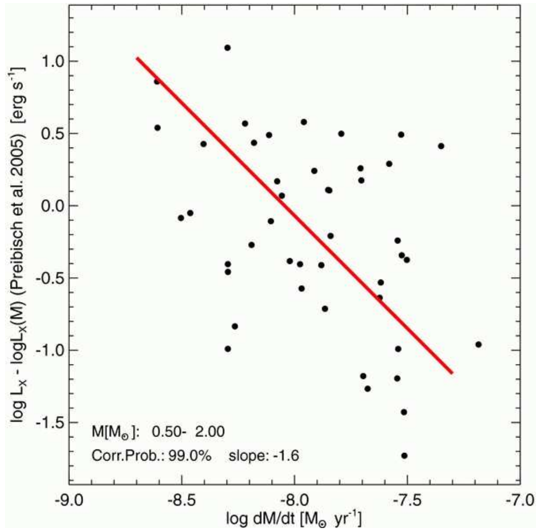

Figure 2: Reproduction of Fig. 3 from Drake, Ercolano, et al. (2009), showing the anti-correlation between X-ray luminosity and accretion rate.

d) The new model of photoevaporation-starved accretion

While the previous models were based on the idea that accretion somehow suppresses, disrupts or obscures coronal X-ray activity, Drake et al. (2009) developed an alternative model by suggesting that the X-rays may instead modulate the accretion flow. They explained this effect with the X-ray heated accretion disk models of Ercolano et al. (2008a,b, 2009) and showed that photoevaporative mass-loss rates of disks are strongly dependent on stellar X-ray luminosity and sufficiently high to be competitive with accretion rates. As described in more detail below, the strength of the coronal X-ray emission determines the accretion rate, and stars with strong X-ray emission should accrete at lower rates because their disks suffer from higher photo-evaporative mass-loss rates. This implies that the stellar X-ray activity controls the evolution of the disk, and thus should have far-reaching consequences, e.g. on the process of planet formation and on the disk dissipation timescale.

As a first test of this new theory, Drake et al. (2009) compared X-ray luminosities and accretion rates for stars in the Orion Nebula Cluster and found an anti-correlation between these two quantities (see Fig. 2). However, these conclusions remained tentative, because they were based on a rather small sample of just 44 stars, for which accretion rate estimates were available at that time. Because of the fundamental importance of this theory, the relation between X-ray activity and disk accretion should be tested in much more detail.

e) Disk Dispersal by Photoevaporation

Theoretical arguments clearly suggest that photoevaporation driven by the ionizing radiation from the central young star is the most important mean for the dispersal of disks (see Alexander et al. 2014, for a recent overview). A simple outline of the physical mechanism is as follows: The high-energy radiation from the star ionizes the H atoms in the surface layer of the disk and thereby heats this gas to temperatures of typically 10 000 K. At radii where the corresponding sound speed of the heated gas ($\sim$ 10 km/s) is similar or larger than the escape speed from the gravitational well (typically a few AU), the hot gas is then essentially unbound; it can stream away and escape from the disk in the form of a thermally driven wind.

This mass loss from the outer disk interrupts the supply of material into the inner parts of the disk,

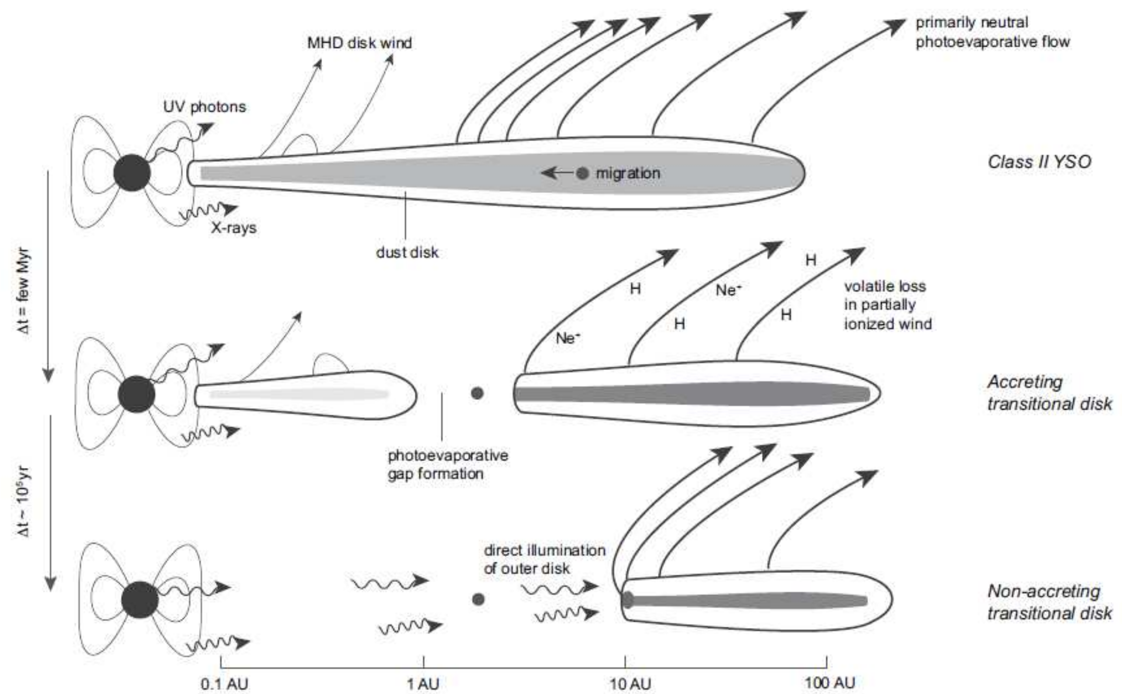

Figure 3: Illustration of major steps in the evolution of a circumstellar accretion disk from the CTTS phase to the formation of an inner hole and up to the complete dispersal of the disk (from Alexander et al. 2014).

which is still viscously accreting onto the star. As illustrated in Fig. 3, this leads to the formation of a hole in the inner regions of the disk. In the following phases, the outer disk (which is now fully exposed to the stellar irradiation, because the shielding from the inner disk does no longer exist) is finally fully dispersed on rather short timescales. This sequence of evolutionary steps is illustrated in Fig. 3.

Until a few years ago, it was generally assumed that the stellar EUV radiation (similar to the chromospheric emission from our Sun) is the dominant agent of disk dispersal (Alexander et al. 2006). For the typical EUV fluxes of roughly solar-mass young stars ($\sim 10^{41}$ photons per second), mass-loss rates of $\dot{\mathrm{M}} \sim 3 \times 10^{-10}\,\mathrm{M}_\odot/\mathrm{yr}$ have been estimated in numerical simulations. These mass-loss rates are limited by the fact that the stellar EUV photons can penetrate only to very small values of the gas column density ($N_\mathrm{H} \sim 10^{18}\,\mathrm{cm}^{-2}$), because the photo-absorption coefficient for EUV radiation is very high. Therefore, the EUV radiation can ionize only a thin surface layer of the disk, where the gas density is quite low.

Only recently it became clear that stellar X-ray photons are considerably more efficient in producing disk winds (Ercolano et al. 2008a,b, 2009). The fact that the typical fluxes of X-ray photons (roughly 10^{39} photons per second) are considerably lower than the EUV photon fluxes, is offset by the much larger penetration depth of X-ray photons compared to EUV photons. As the photo-absorption coefficient for keV photons is 4 to 5 orders of magnitude lower than for EUV photons, the X-rays can reach much further down into the deeper layers of the disk (up to $N_\mathrm{H} \sim 10^{24}\,\mathrm{cm}^{-2}$), where the disk densities are much higher. Therefore, the X-ray driven disk wind starting from these denser regions closer to the disk midplane can produce much higher mass-loss rates, around $\dot{\mathrm{M}} \sim 3 \times 10^{-8}\,\mathrm{M}_\odot/\mathrm{yr}$ for the typical X-ray fluxes of young stars.

The temporal evolution according to this model depends sensitively on the flux and the spectrum of the X-ray photons and the resulting strength of the driven disk wind.

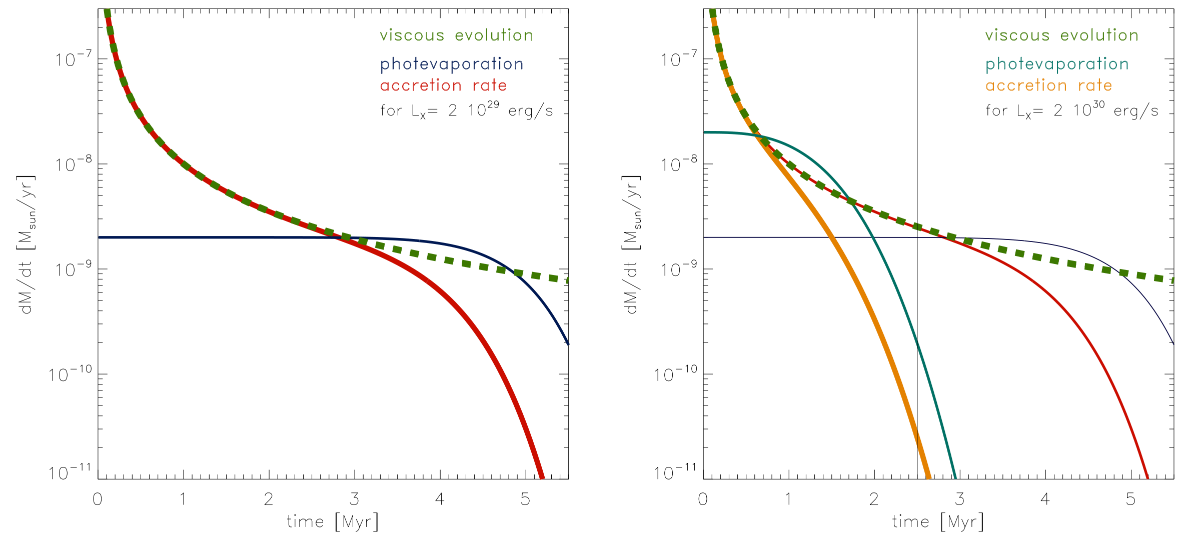

Figure 4: Illustration of the temporal evolution of photoevaporative wind mass loss rate and accretion rate according to the scenario of X-ray photoevaporation-starved accretion. The **left plot** shows the case of a TTS with moderate X-ray luminosity of 2×10^{29} erg/s. The thick dashed green line shows the purely viscous accretion rate that would result if there were no photoevaporation. The dark blue line shows the mass loss rate resulting from X-ray photoevaporation, and the thick red line the actual accretion rate.
In the **right plot**, model curves for the case of a 10 times higher X-ray luminosity are added. Comparison of the curves for the accretion rate in both cases (dark red and orange lines) at the age of 2.5 Myr (solid vertical line) illustrates the much lower accretion rate of the high X-ray luminosity case compared to the low X-ray luminosity case.

1.1 Project-related publications

Kees to Thomas: Please add some text in each of the 10 publications below to argue what their relevance is to this project.

Th. Preibisch, Y.-C. Kim, F. Favata, E.D. Feigelson, E. Flaccomio, K. Getman, G. Micela, S. Sciortino, K. Stassun, B. Stelzer, H. Zinnecker, 2005, *The Origin of T Tauri X-ray Emission: New Insights from the Chandra Orion Ultradeep Project*, Astrophys. Journal Supplement (COUP Special Issue), 160, 401–422

Th. Preibisch, E.D. Feigelson, 2005, *The evolution of X-ray emission in young stars*, Astrophys. Journal Supplement (COUP Special Issue), 160, 390–400

Th. Preibisch, S. Hodgkin, M. Irwin, J.R. Lewis, R.R. King, M.J. McCaughrean, H. Zinnecker, L. Townsley, P. Broos, 2011, *Near-Infrared properties of the X-ray emitting young stellar objects in the Carina Nebula*, Astrophys. Journal Supplement, 194, 10

J.J. Drake, **B. Ercolano**, E. Flaccomio, G. Micela, 2009, *X-ray Photoevaporation-Starved T Tauri Accretion,* Astrophysical Journal Letters, 699, L35–L38

B. Ercolano, 2014, *The dispersal of protoplanetary discs,* Astronomische Nachrichten, 335, 549

J.E. Owen, C.J. Clarke, **B. Ercolano**, 2012, *On the theory of disc photoevaporation,* Monthly Notices of the Royal Astronomical Society, 422, 1880–1901

J.E. Owen, **B. Ercolano**, C.J. Clarke, 2011, *Protoplanetary disc evolution and dispersal: the implications of X-ray photoevaporation,* Monthly Notices of the Royal Astronomical Society, 412, 13–25

B. Ercolano, D. Mayr, J.E. Owen, G. Rosotti, C.F. Manara, 2014, *The $\dot{M} - M_*$ relation of pre-main-sequence stars: a consequence of X-ray driven disc evolution,* Monthly Notices of the Royal Astronomical Society, 439, 256–263

C.F. Manara, **L. Testi**, 2014, *The imprint of accretion on the UV spectrum of young stellar objects: an X-Shooter view,* Astrophysics and Space Science, 354, 35-39

C.F. Manara, G. Rosotti, **L. Testi**, et al., 2016, *Evidence for a correlation between mass accretion rates onto young stars and the mass of their protoplanetary disks,* Astronomy & Astrophysics, 591, L3

2. Objectives and work programme

2.1 Anticipated total duration of the project

3 years

2.2 Objectives

The main objective of this project is to establish the role played by stellar X-ray radiation in shaping the accretion rate distributions of Type I transition discs. The model of photoevaporation-starved accretion makes quite specific predictions on the temporal evolution of the disk accretion rate as a function of the strength of the X-ray irradiation (Drake et al. 2009; Owen, Ercolano & Clarke 2011). As illustrated in Fig. 4, the model predicts that as soon as the viscous accretion rate drops to values comparable to the wind mass-loss rate due to photoevaporation, an inner disk gap and then a hole forms (i.e. the disk becomes a Type 1 TD) and the accretion rate onto the star will drop strongly within a short period of time. This predicts that a higher X-ray luminosity should lead to an earlier formation of the inner disk hole. At a given time, stars with higher levels of X-ray activity should therefore display lower accretion rates.

The immediate objective of this project is to test these model predictions with more, and especially more reliable, observational data. This is very timely now, because during the last few years, the availability of data required for reliable accretion rate determinations has improved very substantially. This is to a large degree related to the recent advent of new powerful spectrographs like X-SHOOTER at the VLT, that combine high spectral resolution with a very wide wavelength coverage (the entire optical and near-infrared range, in the case of X-SHOOTER). Several spectroscopic surveys of young stars in different regions have been performed in the last few years or are ongoing and provide a wealth of new, high-quality data, which can be exploited now (see Manara & Testi 2014).

2.3 Work programme including proposed research methods

In this project, we aim at combining the numerous available deep X-ray observations of star forming regions in the *Chandra* and XMM data archives with new and reliable measurements of the accretion rates of young stars in these regions. We want to build up a large sample of young stars of different mass and age, for which we then can perform a detailed statistical analysis of the relation between X-ray activity and accretion in mass- and age-stratified stellar sub-samples.

This was not possible in the past, because accretion rates determinations were only available for few stars, and even when available, the results were often plagued by large uncertainties. The main problem with most previous accretion rate estimates was that they were usually based on color excesses or equivalent-width determinations of single tracer lines (such as Hα). The other important parameters, i.e. the stellar effective temperature and the extinction, which are needed to convert color excesses or equivalent-widths to accretion rates, had to be derived from separate observations, or (more usually) collected from the literature. This combination of different observational data can easily lead to substantial uncertainties in the derived accretion rate estimates and the stellar parameters. A good example of this is the study of Orion Nebula Cluster stars by Robberto et al. (2004), who determined accretion rates for a sample of 40 young stars in the Trapezium cluster from Hubble Space Telescope *U*- and *B*-band photometry. As the computation of the accretion parameters from the UV excess involves numerous assumptions, their values had considerable uncertainties; for 25% of their stars, they found even negative (i.e. unphysical) values for the accretion luminosities.

The most important advantage of the new high-resolution wide-wavelength range spectra is that they allow a self-consistent and simultaneous determination of all the important parameters, i.e. the stellar effective temperature, the extinction, and the accretion rate, at the same time and from one coherent data set. This results in a far more reliable determination of accretion rates (see Manara & Testi 2014).

The recent study of Manara et al. (2013) provides a very good illustration of this fundamental aspect: They investigated two stars in the Orion Nebula Cluster for which previous data suggested a very strange combination of quite old ages ($>$ 10 Myr) and rather high accretion rates (as estimated from the equivalent width of the Hα line). Manara et al. used VLT/X-SHOOTER spectra combined with an accurate method to re-determine the stellar parameters and the ages of the targets in a self-consistent way. The results of their analysis showed that the earlier studies had strongly underestimated the extinctions and thus the luminosities of these two stars. With the new extinction, luminosity, and accretion rate values derived from X-SHOOTER, these two stars could be shown to be in fact rather typical accreting young stars, and not mysterious “old accretors” as claimed before.

As described below in more detail, a brief scan through the available X-ray archive data and matching recent reliable accretion-rate determinations from the literature suggests that it will be possible to construct a sample consisting of several hundred young stars. This number is already much larger than the sample-size of 44 objects, on which the above described previous statistical study was based, which yielded strong hints, but no really statistically significant proof for an anti-correlation between X-ray luminosity and accretion rate.

We also plan to actively enlarge the sample of stars with reliable accretion rate measurements by 1) re-analyzing existing X-SHOOTER spectra in the ESO archive in order to derive accretion rates in a consistent way, and 2) performing new X-SHOOTER spectroscopic observations of young stars in selected clusters.

In this way we will assemble a large, comprehensive, and consistent database on accretion and X-ray data for YSOs with a wide range of stellar masses and ages. With an expected final sample of several hundred objects we can then perform a detailed statistical analysis of the relation between X-ray activity and accretion in mass- and age-stratified sub-samples of young stars. The results will provide crucial new constraints for theoretical models of the X-ray-disk interaction by photoevaporation and allow us to draw conclusions on the expected accretion rate distributions of young stars.

2.3.1 Work programme including proposed research methods

The work programme consists of three blocks in which high-quality data on the accretion rates and X-ray luminosities of young stars are collected, and a final block for the statistical analysis and comparison to the theoretical models.

In the first block, we want to perform a detailed study of the $\sim$ 700 young stars in the Orion Nebula Cluster, for which new and reliable accretion rate data are now available (part 1a). In this analysis, we will also investigate the possible effects of variability of the accretion rates as well as the X-ray luminosities on the correlation between these two parameters (part 1b). Furthermore, using new optical spectroscopic data from recent X-SHOOTER and MUSE observations of Orion Nebula Cluster stars, we want to increase the sample of stars with accretion rate determinations (part 1c).

In the second part of the project we will use the existing X-SHOOTER spectra for numerous young stars in various star forming regions to derive new and self-consistent measurements of the stellar parameters and the accretion rates. We will determine X-ray luminosities of these stars and then use these new data, as well as published results, for a statistical analysis. This will allow us to extend the investigation to stars that are younger or older than the stars in the Orion Nebula Cluster.

In the third part of the project, we plan to obtain new X-SHOOTER spectra for selected stars in order to increase the sample and to optimize the coverage of the parameter space with respect to stellar age and mass.

In the final part of the project, all these data will be statistically analyzed and used to test the theoretical models.

Project Part 1: Orion Nebula Cluster

The first target for this study will be the Orion Nebula Cluster, for which the COUP data provide the most sensitive and complete X-ray data set on a sample of about 1000 young stars.

Part 1a: Correlation analysis of the existing X-ray and accretion data

The first step in the work will be to use the new accretion rates that have been determined for $\sim$ 700 young stars in the Orion Nebula Cluster from Manara et al. (2012) and correlate them with the available X-ray data from the COUP project. Manara et al. (2012) derived accretion rates from both the U-band excess and the Hα luminosity, after determining empirically both the shape of the typical accretion spectrum across the Balmer jump and the relation between the accretion luminosity and the Hα luminosity. Their tables also report fundamental stellar parameters such as the effective temperature, extinction, luminosity, radius, and the age. This is particularly important, since it makes sure that the data on accretion rates are consistent with the stellar parameters.

This stellar sample will be cross-correlated with the COUP source table, that lists the X-ray properties of the 1616 X-ray detected objects in the Orion Nebula Cluster. Due to the large sample size, this will allow already a much more detailed statistical analysis of the relation between X-ray activity and accretion properties in mass- and age-stratified samples than possible before.

Part 1b: Investigating the effects of variability

The known variability of the X-ray emission as well as the temporal variability of the accretion rates is a potential complication for the investigation of the relation between X-ray emission and accretion, given the fact the X-ray and accretion rate measurements are usually not obtained simultaneously. For the case of the ONC, the COUP X-ray observations were performed in January 2003, whereas the HST observations, from which the accretion rates have been determined, were carried out between October 2004 and April 2005. We therefore have to take into account the typical amplitudes of variations on timescales of a few years, and consider the corresponding possible effects on the correlation analysis.

X-ray luminosities of young stars show typical variations of about a factor of 2 on timescales of months to years (e.g. Wolk et al. 2004). Stronger variations can, of course, occur if the star happens to show a particularly strong X-ray flare during the observation. However, these flares can easily be recognized by inspection of the X-ray lightcurve. In the case of the COUP data set, the derived X-ray luminosities provide an average over more than 10 days, i.e. more than one rotation period for almost all of these stars. Since lightcurves have been analyzed and objects with strong flares during the observation are known, this information can be used in the statistical analysis.

As described in the introduction and illustrated in Fig. 1, the variability of the accretion rates in YSOs is strongly dependent on the age and evolutionary state of the objects. Very strong variability is expected during the very young, protostellar stages. At the typical ages of our target stars (about 1 to 5 Myr), accretion rate variability is much more moderate than during the very young phases. An important quantification of the typical accretion variability of T Tauri stars was recently provided by the detailed monitoring study of Venuti et al. (2014) and Venuti et al. (2015). They found that the variability of the accretion luminosity, as traced by UV excesses, typically amounts to a factor of $\sim 2-3$ on timescales from weeks to several years. This amplitude of accretion variability is thus clearly much smaller than the large scatter (two to three orders of magnitude) seen in the distribution of the accretion rates of the cluster stars. This result shows that the observed wide range of accretions rates in a young cluster is **not** primarily due to accretion variability, but rather reflects the large range of individual accretion rates of the individual stars. This supports the model we want to test in this project, i.e. that the accretion rate of individual YSOs depends sensitively on the high-energy emission of the central star.

The results from Venuti et al. (2014) are consistent with numerous monitoring studies of YSOs, which also trace the accretion variability as one part of the total photometric variability of a YSO. These studies generally found that the typical amplitudes of photometric variability of YSOs in the TTS stage are not more than a few tenths of a magnitude (i.e. about a factor of two) on timescales from days to several years. For the case of the Orion Nebula Cluster, several studies of optical variability on timescales between a few hours and several years have been performed during the last years (Herbst et al. 2002; Stassun et al. 2006, 2007; Parihar et al. 2009; Rice et al. 2015) and confirmed the generally quite moderate levels of variability. For the large majority of the monitored stars, the observed brightness variations were well below about 0.5 magnitudes.

The recent determination of the frequency of strong accretion rate outbursts for YSOs by Hillenbrand & Findeisen (2015) also fits into this picture: while the accretion outburst frequency may be as high as $10^{-3}\,\mathrm{yr}^{-1}\,\mathrm{star}^{-1}$ for very young ($\leq$ 0.25 Myr old) protostars, it drops to just about $3 \times 10^{-6}\,\mathrm{yr}^{-1}\,\mathrm{star}^{-1}$ for $\geq$ 1 Myr old TTS (which are the targets in our project). This suggests that in a sample of $\sim$ 1000 TTS, the likelihood to catch a significant accretion outburst on at least one star in a 10 year period (i.e. the upper limit for the time difference between the X-ray and accretion rate observations) is just a few percent.

To summarize, these results are consistent with the assumption that the time difference between the X-ray and accretion rate observations should lead to uncertainties that are not much larger than about a factor of $\sim 2-3$ in the accretion rate values for most stars. While this will increase the scatter in the relations between X-ray emission and accretion rate, it does not constitute a fundamental problem for a statistical analysis. The few stars that showed stronger variability in the available monitoring studies can be excluded or treated separately in our correlation study.

Nevertheless, it cannot be excluded that some objects have perhaps undergone a larger variation of the accretion luminosity since the time of the X-ray observation. In order to identify such possible cases in the Orion sample, we have recently started a multi-year and multi-color photometric monitoring project. The aim of this project is to identify stars that show significant brightness variations indicative of strong accretion rate variability on timescales from months to years. These observations are performed with our own (LMU) 2m Fraunhofer Telescope on Mount Wendelstein. The new wide-angle camera WWFI (providing a 0.5° field-of-view) is ideally suited for this monitoring project, since it allows to cover the entire cluster, including the full field of the COUP X-ray observation ($17' \times 17'$), in one exposure. Figure 5 shows a first test image of the ONC obtained with WWFI with an overlay of the COUP field. A first and preliminary analysis of these test images shows that more than 450 of the X-ray detected young stars are bright enough (in comparison to the surrounding nebulosity) to allow a photometric monitoring with these data.

We plan to obtain optical images in up to three bands about every second week during the season of observability. Over the 3-year period of the proposed project, this will yield a comprehensive dataset for a photometric analysis of long-term variability. This will thus allow us to identify objects that show a strong variation of their brightness on a multi-month to multi-year timescale. Stars with strong variability on even longer timescales can also be identified by comparing the photometry from our Wendelstein observations with older literature data. If any such highly variable objects are identified, they can be excluded (or treated separately) in the statistical correlation analysis between X-ray emission and accretion.

Part 1c: New accretion rates for ONC

Nineteen young stars in the Orion Nebula cluster have already been observed with X-SHOOTER. We will use these data to derive accretion rates for these stars. This will allow a detailed comparison with the above mentioned accretion rate determinations and increase the size of the sample, for which we can correlate accretion and X-ray data.

Another very interesting spectroscopic dataset was recently obtained with the ESO Multi Unit Spectroscopic Explorer (MUSE), an integral-field spectrograph operating in the visible wavelength range at the ESO 8m Very Large Telescope. The MUSE consortium has released data cubes and maps of the Huygens region of the Orion Nebula published by (Weilbacher et al. 2015). These data provide a spatial sampling of $0.2''$ per pixel, a spectral resolution of 0.85 Å per pixel, and cover the wavelength range 4595 Å to 9366 Å. We have retrieved and inspected these data, and found that useful optical

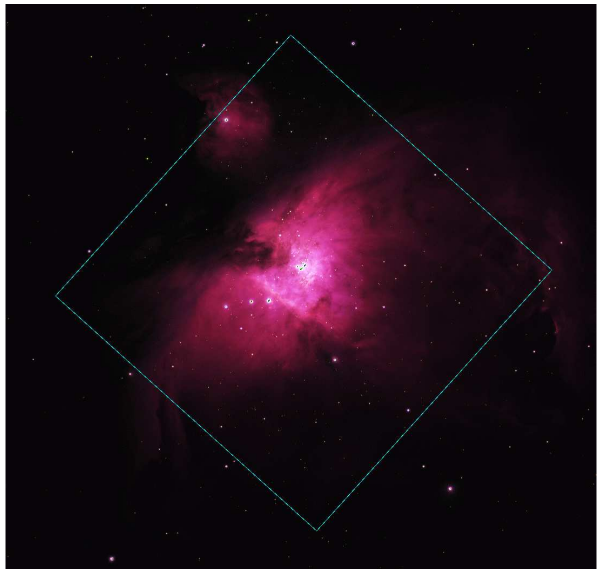

Figure 5: Optical image of the ONC obtained with the WWFI camera at our 2m Fraunhofer Telescope on Mount Wendelstein. The image is a three-color composite of *g*-band (blue), *r*-band (red), and *i*-band (green) exposures. The cyan rectangle shows the $17' \times 17'$ field of the COUP X-ray observation.

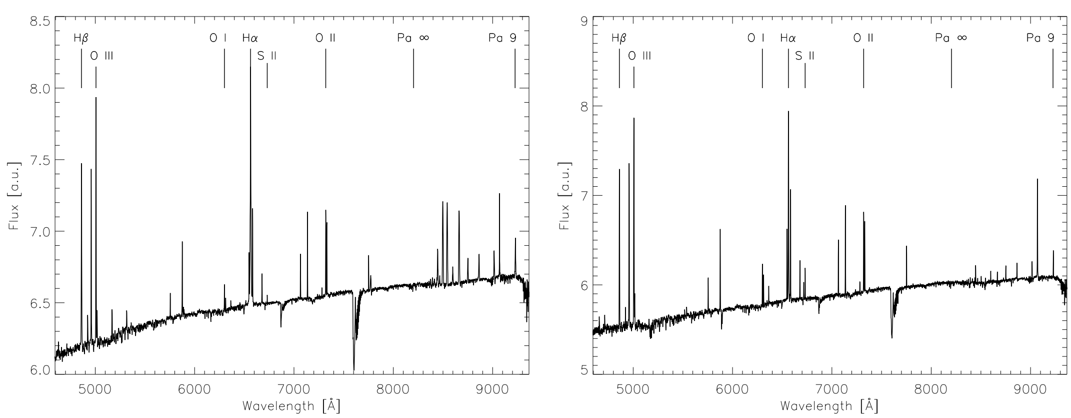

Figure 6: Spectra of two stars (COUP 758 and COUP 855) extracted during our preliminary analysis of the MUSE data cube of the Orion Nebula.

spectra can be extracted for at least 359 of the COUP X-ray sources. Two examples of objects with strong emission lines, indicative of high accretion rates, are shown in Fig. 6

These MUSE spectra can complement the X-SHOOTER data and thus increase the number of stars with spectroscopic accretion rate determinations. Finally, a comparison of MUSE and X-SHOOTER spectra for stars observed with both instruments can also provide important information on time variability of the accretion rates.

Part 2: New accretion rates for other star forming regions

In the second part of the project, we will extend the analysis to young stars in other star forming regions, for which either reliable accretion rate determinations or X-SHOOTER spectra are available. Correlating these data with *Chandra* and XMM X-ray observations will provide further samples of young stars, in which we can investigate the relation between X-ray luminosity and accretion. This will allow us to extend the parameter space, e.g. by observations of clusters that are somewhat younger or older than the Orion Nebula Cluster.

Reliable accretion rate determinations are available for the following regions:

1) NGC 2264:
Venuti et al. (2014) determined stellar parameters and accretion rates for about 750 YSOs in this cluster. Accretion rates were determined from U-band excess emission as well as emission lines.

This cluster was also extensively studied with *Chandra*: eight deep ACIS-I observations of the different parts of this region are available in the *Chandra* data archive.

2) IC 348:
Dahm (2008) performed a spectroscopic investigation of accretion diagnostics for 40 near solar mass members of IC 348 and derived accretion luminosities and rates for these stars.

The X-ray properties of these stars are very well known, since IC 348 has been very well observed in X-rays: initially with ROSAT (Preibisch, Zinnecker, & Herbig 1996), with several deep *Chandra* observations (Preibisch & Zinnecker 2002; Stelzer, Preibisch. et al. 2012) and also with XMM-NEWTON (Preibisch & Zinnecker 2004).

Reliable accretion rate determinations and/or X-SHOOTER spectra are also available for:

3) the sigma Ori cluster (accretion rates from U-band photometry from Rigliaco et al. (2011); X-SHOOTER spectra for 10 stars)

4) the ρ Ophiuchi region (accretion rates for 104 stars from Natta et al. (2006); X-SHOOTER spectra for 17 YSOs from Manara et al. (2015))

5) the Lupus region (accretion rates for 36 YSOs from X-SHOOTER spectra by Alcalá et al. (2014))

6) the Chamaeleon I region (accretion rates from X-SHOOTER spectra by Manara et al. (2016))

7) the Upper Scorpius association (X-SHOOTER spectra for 25 stars)

8) the TW Hya association (X-SHOOTER spectra for 15 stars)

9) the Taurus region (X-SHOOTER spectra for $\sim$ 15 stars).

Deep X-ray observations of all these clusters and associations are available in the Chandra and XMM data archives. We will retrieve these X-ray data and analyze them in a homogeneous way using the most recent analysis tools (like ACIS-Extract for the Chandra data) to detect and characterize X-ray sources. The determination of the X-ray luminosities will be based on a model fitting analysis of the X-ray spectra with CIAO and XSPEC for sources with a sufficient number of source counts. For weaker X-ray sources, the X-ray luminosities can be determined from the observed number and energy of the detected X-ray photons with the `srcflux` tool in the Chandra analysis software. Cross-correlating the resulting X-ray source lists with the catalogs of spectroscopically observed stars will yield the samples for which we can investigate the relations between X-ray activity and accretion.

In order to extend our database to higher stellar masses, we also plan to analyze the available X-ray data for the 91 Herbig AeBe stars (YSOs in the mass range from $\approx 2 - 8\,M_\odot$) for which accretion rates were determined from X-Shooter spectra in the recent study of Fairlamb et al. (2017).

Part 3: New X-SHOOTER observations

In the course of the project, we also plan to perform new observations with X-SHOOTER in order to extend the spectroscopic sample and to optimize the overlap with the X-ray observations.

Part 4: Statistical analysis

The final aim of the observational part of this project is to get as many and as reliable as possible data points to perform detailed statistical analysis of the relation between X-ray activity and accretion in mass- and age-stratified samples of young stars in different young clusters. This will provide crucial new constraints for theoretical models of the X-ray-disk interaction.

The earlier theories (described in Sect. 1c) that tried to explain how accretion somehow may reduce the X-ray emission, could not make testable predictions. The proposed effects (like changes in the coronal magnetic field structure by the accreted material, stripping of the coronal magnetic field by the interaction with the disk, or a reduced differential rotation in the star due to magnetospheric coupling) would depend very sensitively on the details of the interaction. The resulting reduction of the X-ray luminosities could be quite strong, but also rather weak, and should thus essentially introduce scatter in the relations between the X-ray properties and accretion properties.

The Drake, Ercolano, et al. (2009) model, however, makes a rather clear prediction that the observed accretion rate for stars at a given age should scale inversely proportional to the X-ray luminosity. This direct relation between accretion and X-ray luminosity for stars of a given age can be tested with the observational data in different stellar mass and age regimes.

2.4 Data handling

All required tools for analyzing the X-ray and optical data are available.

2.5 Other information

none

2.6 Information on scientific and financial involvement of international cooperation partners

none

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4. Requested modules/funds

4.1 Basic Module

4.1.1 Funding for Staff

We ask for one PhD position for three years.

4.1.2 Direct Project Costs

[Text]

4.1.2.1 Equipment up to EUR 10,000, Software and Consumables

none

4.1.2.2 Travel Expenses

[Text]

4.1.2.3 Visiting Researchers (excluding Mercator Fellows)

[Text]

4.1.2.4 Other Costs

[Text]

4.1.2.5 Project-related publication expenses

[Text]

4.1.3 Instrumentation

none

4.1.3.1 Equipment exceeding EUR 10,000

none

4.1.3.2 Major Instrumentation exceeding EUR 100,000

none

4.2 Module Temporary Position

not relevant

4.3 Module Replacement Funding

none

4.4 Module Mercator Fellows

none

4.5 Module Public Relations Funding

Kees to Barbara: I think public relations should go into the main part of the Forschergruppe proposal.

5. Project requirements

5.1 Employment status information

Thomas Preibisch, Professor at the Ludwig-Maximilians-Universität München (permanent)
Barbara Ercolano, Professor at the Ludwig-Maximilians-Universität München (permanent)
Leonardo Testi, Faculty Member at the European Southern Observatory (permanent)

5.2 First-time proposal data

not applicable

5.3 Composition of the project group

[Text]

5.4 Cooperation with other researchers

5.4.1 Planned cooperation on this project

5.4.1.1 Collaborating researchers for this project within the Research Unit

Please summarize here how this project is linked to the other RU projects.

5.4.1.2 Collaborating researchers for this project outside of the Research Unit

Please summarize here how this project is linked to international teams.

5.4.2 Researchers with whom you have collaborated scientifically within the past three years

Please just provide a list of names. Maybe you can boldface those whom you work with closely.

5.5 Scientific equipment

none

5.6 Project-relevant interests in commercial enterprises

none

5.7 Additional information

none