# Research plans

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Classical Novae are the third-most violent explosions in the universe and have important implications for the evolution of white dwarfs in general and for the progenitors of Supernovae Ia in particular, as well as the composition of the interstellar medium. Studies of Stellar Coronae allow conclusions about the importance of stellar parameters on the generation of coronae, in particular the solar corona. Both research areas benefit greatly from observations in X-rays, especially high-resolution X-ray spectroscopy. In Stellar Coronae we observe X-ray emission lines, while in Classical Novae we see absorption line spectra.

## 1 Introduction: Motivation of Research areas

• **The outbursts of Classical Novae**

*Background:*

Classical Novae (CNe) occur in accreting white dwarf/main sequence binary systems, when accreted material ignites in a thermonuclear explosion. The bolometric luminosity is high enough to drive a radiatively driven wind and is assumed to be constant until nuclear burning discontinues. Early in the outburst the energy output occurs in optical light as a result of the high opacity within the expanding shell not permitting the high-energy radiation produced by nuclear burning to escape directly ($e^-$ scattering). During the evolution, clearing of the shell leads to the peak of the spectrum to gradually shift to higher energies until a supersoft X-ray spectrum is observed (SSS phase). This is the only time that the physical processes happening in the outburst can *directly* be observed. The strategic importance of Nova outbursts arises from:

⋆ The ejected material has undergone nuclear processes and enriches the interstellar medium. The observed amount of ejected material is larger than anticipated from theoretical models, thus the importance of novae for the chemistry of the Galaxy may be underestimated and play an important role in galaxy evolution.

⋆ Due to the high mass loss the white dwarf effectively looses mass (more than accreted), and Nova outbursts prevent white dwarfs from growing in mass.

⋆ Supernova Ia explosions require a white dwarf that reaches the mass of 1.4 solar masses, and Nova outbursts seem to prevent that to happen. The progenitors of Supernovae Ia are therefore unknown.

⋆ Supernovae Ia are important distance indicators because they always occur under the same conditions (1.4 solar masses) and have the same absolute brightness.

⋆ Outbursts of Classical Novae play a key role in white dwarf evolution.

*Goals:*

⋆ Ultimate goals are to understand the evolution of the outburst, find the Supernova Ia progenitors, and arrive at an accurate description of the contributions of novae to the chemical composition of the interstellar medium.

⋆ Specifically: What is the elemental composition of the ejected material? Determine the mass of the white dwarf before and after the outburst.

⋆ Since Nova outbursts are relatively frequent events, their contribution to the composition of the interstellar medium is considerable.

- ⋆ Theoretical models predict that under certain circumstances, a nova outburst can leave behind a supernova Ia progenitor, and these circumstances can be studied with detailed X-ray observations.

*Challenges:*

- ⋆ All novae observed so far have developed differently, and we have experienced a lot of surprises. No stringent classification scheme is available.
- ⋆ The X-ray spectra are extremely complex and we are only beginning to find sensible atmosphere models that account for radiative transfer *and* the dynamics.

**•Stellar coronae**

In contrast to the solar X-ray corona, stellar coronae cannot be spatially resolved. Despite the ability to study the solar corona in great detail, the formation of the solar corona is still a puzzle. A better understanding will only be possible by observing not just one type of corona, but by comparing coronae formed under different physical conditions.

*Background:*

- ⋆ Characteristics of Solar activity: Sun spots, chromosphere (20,000 degrees, ionized emission lines in UV and optical light), Corona (1 Million degrees, X-ray emission, highly ionized emission lines). For comparison: The solar surface has only 6000 degrees.
- ⋆ The solar surface produces no X-ray emission → X-ray regime ideal for uncontaminated observations of stellar coronae.
- ⋆ Stellar Coronae cover a large range of stellar parameters that can be studied in relation to the formation of coronae.
- ⋆ E.g., the relationship between stellar rotation and X-ray intensity was discovered from studies of samples of stellar coronae, which would have remained undiscovered with studies of the solar corona alone.
- ⋆ Conclusion: Magnetic fields, generated by an internal dynamo, power the corona.

*Goals:*

- ⋆ The ultimate goal is to develop predictive models of the solar corona.
- ⋆ The involvement of magnetic fields (particularly if they are inhomogeneous) is extremely challenging to developing theoretical models; no coherent theoretical model exists for coronal formation, but improvements from observations allow tests and refinements of existing dynamo theories.
- ⋆ In order to test competing dynamo theories, it is important to obtain detailed descriptions of coronae formed under various conditions.

*Challenges:*

- ⋆ The interpretation of X-ray spectra does not yield unique solutions, and automatic analysis approaches need to be backed by careful inspection with a great deal of intuition.
- ⋆ The existing atomic data are incomplete but are being improved. Careful studies are required to investigate the implications of future improvements on the results.
- ⋆ Stellar coronae cannot be spatially resolved, and one has to think about how a heterogeneous stellar corona forms a net spectrum resulting from contributions by the various features.

# 2 Summary of past and present research

My main research areas are motivated above. I have also accomplished the first detection of X-ray emission from Saturn, and I have studied galaxies from a theoretical point of view. I describe my past activities by highlighting the results of a few strategic papers in each field, referring to the numbering scheme in the publication list.

## Classical Novae

In [21] I studied a *Chandra* LETG spectrum of V4743 Sgr.

- ⋆ Clear signs of periodic oscillations in the X-ray light curve were found pointing to the rotation period of the white dwarf.
- ⋆ During the observation the X-ray emission level suddenly dropped to almost zero.
- ⋆ The spectrum was first similar to a SSS (bright continuum with absorption lines) and changed then to a faint emission line spectrum (lines radiatively and collisionally excited).
- ⋆ The absorbed continuum spectrum can be modeled with the PHOENIX code ([10]).

In ([5]) I have analyzed a *Chandra* LETG spectrum of V382 Vel that had been observed two months after the source was still bright in X-rays.

- ⋆ Only a faint continuum can be seen, and strong emission lines dominate the X-ray spectrum. The nova must have turned off within two months and we have observed the radiatively cooling expanding shell.
- ⋆ The emission line fluxes can be used to constrain abundances .
- ⋆ At least three different line profiles were found showing a complex velocity pattern.

The nova event of the year 2006 was the outburst of the recurrent nova RS Oph (every $\sim$ 20 years), and more than 70 *Swift* observations were taken and seven *Chandra* and *XMM-Newton* grating observations. I am working on two papers, one is in press ([1]):

- ⋆ During the first month, the spectrum consisted of a Bremsstrahlung continuum with overlying emission lines and originated from a shock moving into the wind and outer atmosphere of the companion and backwards into the ejecta.
- ⋆ From seven grating observations I determined the evolution of temperatures, volume emission measures, and radial velocities *with reliable uncertainties* (only possible with grating spectra).
- ⋆ The second month of the evolution was dominated by the SSS spectrum.
- ⋆ I developed a model that determines column densities and expansion velocities for the shell surrounding the white dwarf.
- ⋆ I discovered complex structures in the K-shell absorption edge (see Fig. 1). The combined effects from the interstellar and circumstellar medium need yet to be disentangled.

- ⋆ The contributions from residual shock emission and the SSS emission can only be disentangled from the grating spectra.

I am also working with *Swift* data and am actively participating in the planing of the observations of novae. I have published the first refereed paper on all *Swift* observations of novae ([2]). A particularly interesting object is the old Nova V723 Cas which is still in outburst. *Swift* has obtained five observations, and I am finalizing an ApJ letter.

## X-ray High-resolution Spectroscopy of Stellar Coronae

In this field I have published nine refereed papers as first author and two review papers ([11]; [39]).

- ⋆ Surveys of line ratios yielding average temperatures and densities lead to volume filling factors ([25]; [13]).
- ⋆ Development of the customized line fitting program CORA ([28]), which includes rigorous conservation of Poissonian statistics according to Cash (1979), ApJ 228, 939
- ⋆ First X-ray density measurements in the coronae of Procyon and Capella ([31]).
- ⋆ Specific solutions for the influence of stellar UV radiation fields on X-ray diagnostics ([45]; [46]).
- ⋆ Systematic assessment of the spectral region around the heavily blended Ne IX triplet, which provides the community with important recipes on how to measure the highly important Ne IX lines ([20]; → also useful in other areas of research).
- ⋆ First discovery of enhanced N/C ratios in stellar coronae implying that nuclearly processed material has been dredged up to the surface of evolved stars ([30]).
- ⋆ Spatial resolution of a limb-flare on Algol from lightcurve reconstruction ([19]).
- ⋆ Studies of the FIP[1] effect in the coronae of $\alpha$Cen and Procyon ([23]; [27]).
- ⋆ Extensive samples of stellar coronae.
  - Investigation of effects of scattering of resonance line photons ([22]).
  - Measurement of densities and estimates of volumes and filling factors ([25]; [13]).
- ⋆ Development of a new approach to obtain the temperature structure independently of elemental abundances ([18]).
- ⋆ Disentangling effects from an accretion shock from normal stellar coronae in classical T Tauri stars ([3]; [4]; [9]; [34]).

[1] In the solar corona elements with low first ionization potential (FIP) are overabundant (Meyer 1985, ApJS 57, 173).

## X-ray Emission from Saturn

The brightest solar-system X-ray source besides the Sun is Jupiter, but the origin of X-ray emission is still unknown. *Chandra* found Jupiter's emission concentrated near the poles, indicative of auroral emission. In a detailed study of X-ray emission from the outer planets, I discovered a small excess of X-rays above the background in a short ROSAT PSPC observation of Saturn [32]. This detection was confirmed with a 70-ks *Chandra* ACIS-S3 observation that I proposed [14] and with a 20 ks observation with *XMM-Newton* [15]. I found

- ⋆ A concentration of X-ray emission near the center of the optical disk.
- ⋆ The level of emission is similar to equatorial emission from Jupiter.
- ⋆ A deficiency of X-rays at both poles (north pole was occulted by the rings).
- ⋆ The spectrum is very faint; consistent with an incident solar spectrum plus some fluorescence.

A later paper by Bhardwaj et al. (2005, ApJ, 624L, 121 which I refereed), confirmed that Saturn's X-ray emission is reflection of solar X-rays. My publication [14] received a great deal of publicity, e.g., NASA press release, astronomy picture of the day (ap040312), USA Today article, Nature (Nature 428, 272). Such high degree of publicity is what I like most about astronomy, and public outreach is one of my favorite tasks. I have been involved in other press releases and a life interview on German television.

## Modeling Disk Galaxies interacting with Satellite Galaxies

During my undergraduate time I have carried out N-body simulations of interacting galaxies. The aim was to find out, whether star formation can be triggered by *Minor Mergers* (interaction of disk galaxies with satellite galaxies as, e.g., Milky Way and LMC). The start models were based on those developed by Kuijken & Dubinski (1995, MNRAS 277, 1341), and gravitational interactions were calculated with a TREE code (Barnes & Hut 1986, Nature 324, 446) with a fraction of particles representing the gas content ("cloud"-particles, undergoing mergers with each other; sticky particle scheme by Theis & Hensler 1993, A&A 280, 85). My task was to implement the inverse process of cloud coalescenes in the form of cloud disintegration that can be interpreted as star formation, and the results are given in [49].

## Summary of technical Expertise

- ⋆ Application of Maximum Likelihood method to low-count spectra; the more popular method is to apply $\chi^2$ fitting after rebinning, however, this approach sacrifices high spectral resolution that has been achieved at a high price.
- ⋆ Detection of weak sources in ROSAT, *Chandra*, *XMM-Newton*, and *Swift* observations.
- ⋆ Computer programming in FORTRAN, C and IDL (see, e.g., [28]). All my research is based on my own programs, I only make use of the instrument specific pipeline procedures provided by SAS (*XMM-Newton*) and CIAO (*Chandra*).
- ⋆ Production of concise figures in IDL for papers and presentations of high quality
- ⋆ Design and maintenance of web pages with html programming

# 3 Future plans

With the great X-ray missions *Chandra* and *XMM-Newton* up and running, we are presently experiencing the most prosperous time of X-ray Astronomy. I am expecting this fruitful period to continue for at least another ten years (near future). Beyond that time I will explore the opportunities of future missions and I am interested in theoretical modelling (e.g. hydrodynamic simulations of nova outbursts).

The present boost in X-ray Astronomy is based on three important improvements over previous missions:

- ⋆ High angular resolution (particularly *Chandra*)
- ⋆ High sensitivity (particularly *XMM-Newton*)
- ⋆ High spectral resolution by use of gratings

Planned future missions focus particularly on higher sensitivity and larger fields of view at higher energies, however, no X-ray mission with higher spectral resolution is planned for the near future, and my skills as an X-ray spectroscopist will not carry me trough my entire life. However, I am urging the *Chandra* director to take provisions to encourage stronger usage of the gratings while *Chandra* is still living and I am being heard. In that way I foresee that I will be able to continue to gather unique insights from high-resolution X-ray spectra in the near future. For the far future I see potentials in stronger engagements in theoretical work, which will benefit from the insights gathered from spectroscopy and the improved computer power by that time. Depending on opportunity I can also work with observations from other wavelength bands and have proven my flexibility in the past. This includes departmental collaborations in any other research area that can benefit from my technical skills.

## Near Future[2]

I anticipate that *Chandra* and *XMM-Newton* will be operating for at least five more years which allows me to continue my activities as X-ray spectroscopist. I will continue to write observing proposals to both missions and explore the existing archival data. The amount of data that has been gathered in the archives to this date cannot be analyzed at the same rate that observations are being carried out, and they provide research material for at least another five years. **The next**

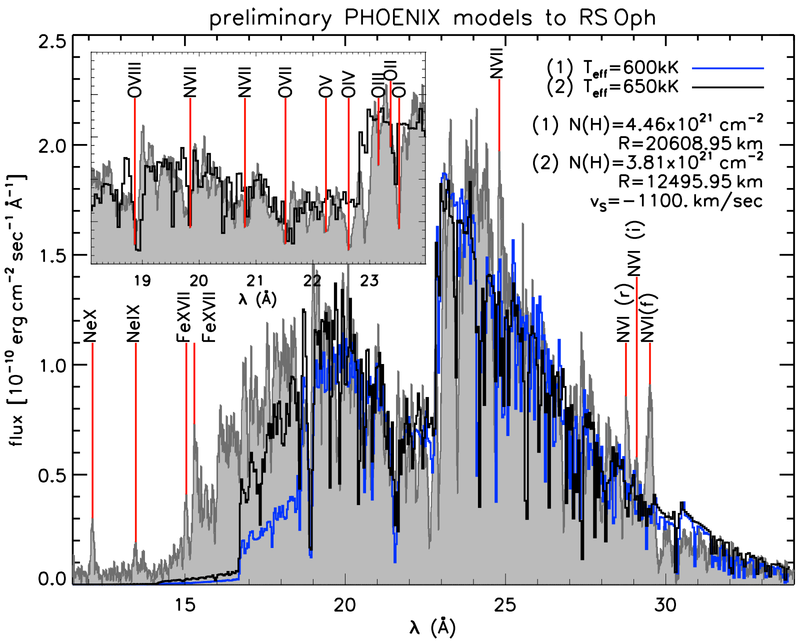


Figure 1: A typical X-ray spectrum of a nova during the SSS phase with two preliminary PHOENIX models.

[2] next 10 years

**10 years will therefore be primarily devoted to High Resolution X-ray spectroscopy of Classical Nova outbursts and Stellar Coronae**. Furthermore, I have occasionally been asked by people from other fields to help them with their grating data (e.g. the field of Cataclysmic Variables), especially so since I have been awarded the Chandra Fellowship. I am thus expecting to be working in a variety of fields that can benefit from my skills which will broaden my horizons. I have also started to engage myself in the analysis of *Swift* data and *Swift* has become an integral part of X-ray observations of novae and will continue to be until the end of the mission.

I now go in some detail describing what can be learnt from high-resolution X-ray spectra. The spectral resolution of grating spectra is sufficiently high to allow studies of individual atomic transitions of highly ionized elements in hot plasmas. In some cases the velocity field can be studied by inspection of line shifts, yielding, e.g., expansion velocities in nova outbursts. The atomic physics behind the grating spectra are complex and atomic databases have not yet reached the quality required for automatic spectral analyzes commonly applied to low-resolution X-ray spectra. In principal, spectral analyzes yield the temperature distribution and the chemical abundances as well as average densities. The nature of the grating spectra being recorded as events files allows time resolved spectroscopy, and all future spectral analyzes can be applied to the spectra extracted from time slices within one observation.

In Fig. 1 I show a typical X-ray spectrum that has been observed with *Chandra* during the bright supersoft (SSS) phase of a nova outburst. This spectrum shows the complexity with a broad continuum, absorption lines and emission lines. My first approach in analyzing such spectra is to carry out a by-eye inspection of spectral regions where strong resonance transitions occur. From pure inspection I can already gather a rough idea about what temperatures and abundances we are dealing with. The second step will be to apply spectral models arising from a set of assumptions based on the previous quick-look analysis. In Fig. 1 I have overplotted two PHOENIX atmosphere models which have been computed based on rough estimates of the temperature, and the continuum is already relatively well represented. However, both models are not physically realistic, e.g., they don't obey energy conservation, not all elements are included, and the atmosphere is static and plane parallel although a nova outburst is expanding and spherically symmetric. A great deal of effort is ahead of us, slowly improving the models along the lines of approaching physically realistic models and the resulting spectra being in best agreement with the observed spectra.

This is a time consuming task, but the parameters obtained from such an atmosphere model give us important clues about

- ⋆ The radial structure of the outflow (velocity, density, temperature).
- ⋆ The absolute abundances from which the amount and composition of the ejected material can be determined.
- ⋆ The surface gravity and thus the mass of the white dwarf.

Within the lifetime of *Chandra* and *XMM-Newton* the observations of bright novae will continue. I give a list of datasets in the archives that I am planning to explore

- ⋆ **V4743 Sgr**
  - Five observations during different times of the evolution. All spectra are like that shown in Fig. 1, and five different PHOENIX models need to be constructed.
  - The spectra extracted from time intervals of maximum and minimum emission during the periodic changes need to be modelled to understand the nature of the variations.
  - There was a sudden disappearance of the continuum source, and the emission line spectrum seen instead will be modelled with Cloudy, yielding the chemical composition of the ejected material.
- ⋆ **RS Oph**: Ten grating observations cover three different phases of the evolution
  - Shock emission: Three spectra will yield the chemical composition and the evolution of the velocity and temperature.
  - SSS phase: PHOENIX models as described above for three spectra. Early in the SSS phase, an unexplained high-amplitude variability was seen that can be probed by extracting spectra during different phases of the variability and compare the best-fit PHOENIX models. Interpolate the PHOENIX models adjusted to the three grating spectra to describe over 40 *Swift* spectra.
  - Nebular phase: Four grating spectra yield abundances and the temperature distribution of the ejecta.
- ⋆ **V1494 Aql**: Three observations during different times of the evolution
  - The SSS spectra are more complex than that shown in Fig. 1 with continuum and strong emission lines on top of the continuum. A combination of PHOENIX models and Cloudy models are required for a full description.
  - A flare occurred during one of the observations, and time resolved spectroscopy can explain the nature of the flare (e.g. increase of temperature or changes of abundances).
- ⋆ **Various supersoft X-ray binary sources (SSS)**:
  - A large number of SSS have been observed with gratings, and, although the same class of objects, are very different from each other.
  - Test whether the SSS are indeed steady nuclear burners (leading to supernova Ia explosions). Questions to address are whether their bolometric luminosities are above the Eddington limit leading to extended atmospheres from a radiatively driven wind.
  - Some SSS are known to turn off for longer periods of time (e.g., Cal 83). Long-term monitoring, e.g., with *Swift* or future X-ray missions can reveal patterns, and trigger *Chandra* observations shortly after they come back to determine spectral changes after a period of silence.

This list is not complete, and more observations of future novae are likely to become available within the next five years. This extensive project can only be carried out by a group of people and I am planning to organize funding for graduate students and post docs. Some of the projects can also be carried out by undergraduate students.

## Far Future

The above described projects are based on the already existing data and are secure for at least ten years. Both, *Chandra* and *XMM-Newton* are operating with no major disruptions and an extension beyond the next five years is not unlikely, such that the spectral analysis of nova outbursts can continue well beyond this time limit. Nevertheless, I have some ideas how I would like to proceed in the case that high-resolution X-ray spectroscopy is explored to its limits without further data being acquired.

A full description of an outburst obtained from grating spectra gives us important constraints to hydrodynamic models of nova explosions. The ejected mass and composition represents the contribution that a given nova injects into the interstellar medium and can be upscaled to estimate the total contribution of novae to the chemical composition of the Galaxy. The variety of different novae yields a distribution of contributions from different types of novae (characterized, e.g., by the type of white dwarf) and can be used to refine such scalings and improve models for the origin of heavy elements in the Galaxy.

A complete and well constrained hydrodynamic simulation can further predict the fate of the remaining system. For example, if the white dwarf remains hot until accretion from the companion resumes, the accreted hydrogen can be fused to helium on arrival at the white dwarf surface. The resulting hydrogen-deficient atmosphere around the white dwarf can continue to accrete matter without a disruptive thermonuclear explosion, gain in mass until the Chandrasekhar limit is reached, and explode as a supernova Ia.

An appointment to a faculty position at my future institute offers me for the first time in my career the opportunity to establish my own working group. I am already working with students who are seeking my supervision, and these would be attracted to my future institute if I was appointed. For example, a student from Munich who holds a very prestigious German/Bavarian stipend would like to do his PhD project under my supervision, but in my present situation I cannot offer him a position as a graduate student when his stipend expires. I will explore all available funds (including European funds for people returning from the US) in order to realize my research ideas. Finally, my past research has demonstrated that I am flexible with engaging in different fields, and I am open to collaborations with other researchers in city of residence. I would also like to get involved with organizing conferences in city of residence.

Specifically, I would fit in well with the *High Energy Astrophysics* group. I am also interested in the composition of the Interstellar medium, which is highly relevant to the interpretation of X-ray spectra. This is not well acknowledged by standard X-ray analyzes, and in collaboration with the *Interstellar matter and star formation* group I see potential to make significant progress on this front.

In a broader context I can use my skills in any other research (or teaching) that requires knowledge of the atomic physics that reflects itself in the X-ray wavelength regime. At my future institute I would use the existing infrastructure to engage in activities that are unique to that city of residence and broaden my horizons.