High-resolution X-ray spectroscopy of Classical Novae and Stellar Coronae

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I currently work in the two research areas of Stellar Coronae and Classical Novae (CNe), focusing on X-ray spectroscopy. On this page I give a short summary of these research areas and go in more detail with two three-page descriptions. Depending on opportunity I plan to expand my observing activities to other wavebands, bringing in the unique potential of X-ray observations into multiwavelength campaigns. I have also spent some thoughts on theoretical modelling. A relatively recent idea that I had is to test the hypothesis that the kind of magnetic dynamos that are thought to power Stellar Coronae may actually be at work during the early stages of nova evolution. While observational evidence for this hypothesis exists, proof for or against this (or other) ideas needs to be collected by means of theoretical considerations and deeper observations.

Studies of Stellar Coronae give us a broader range of stellar parameters relevant for the formation of coronae, a phenomenon that is not understood to this day. Correlations of coronal properties with stellar parameters (e.g., rotation) need to be investigated in order to support theoretical models of the formation of coronae. The solar corona it thought to be powered by a magnetic dynamo that resides in the sheer layers between the rigidly rotating radiative core and the differentially rotating outer convection zone.

Classical Novae are members of the class of Cataclysmic Variables in which an explosion is caused by a thermonuclear runaway in accreted material on a white dwarf (WD). When sufficient material has been accreted by the white dwarf an observable outburst occurs. The emitted radiation comes from the optically thick, expanding, shell of gas. It is initially hot and dense but as it expands it cools and the density drops. As long as the gases are optically thick the system resembles an expanding stellar atmosphere. However, as the expansion continues, the outer layers go optically thin and the photosphere moves inward. The effective radius of the photosphere shrinks with time but the source remains at constant bolometric luminosity so that the effective temperature gradually increases until the peak of the spectral energy distribution moves into the X-ray regime. Spectra taken at this time are classified as those of a Super Soft Source (SSS) since they resemble those of systems such as CAL 83. The evolution of a nova outburst can be pictured as a star gradually stripping off its outer layers until nuclear burning can directly be observed. Monitoring observations in different wavebands at different times of the evolution thus give important insights into stellar structure, and find a climax in X-ray observations reflecting the extreme conditions of nuclear burning.

With the ejection of matter that is partially enriched by dredged up WD material, CNe contribute to the chemical evolution of the interstellar medium, and abundance studies of the ejecta are needed to refine galaxy evolution models. CNe may also be related to the progenitors of supernovae Ia (SN Ia), if they occur in single degenerate systems.

Early in the evolution of some novae, hard X-ray emission has been observed, and the X-ray spectra resemble those of Stellar Coronae. It is possible that a magnetic dynamo, similar to that in the solar corona, is powered by sheer forces on the WD surface, induced by friction between the solid WD surface and the ejected shell. At this stage this scenario is highly speculative, however, the lack of supporting facts is also inherent to the idea of shocks within the ejecta that has been formulated a few years ago. At your Institute I would pursue theoretical approaches as well as systematic observations to collect evidence for or against this idea.

Direct X-ray observations of nuclear burning in Classical Novae

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Abstract

Classical Novae (CNe) 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. CNe also contribute a small fraction of the composition of the interstellar medium. The extreme conditions on the surfaces of white dwarfs are laboratories of nuclear synthesis, and the products of nuclear burning depend primarily on the mass of the white dwarf and the properties of the companion star. However, the observations show that the evolution of novae is more complex and poorly understood. Theoretical understanding can only make progress with more systematic observations in multi-wavelengths. The present X-ray facilities allow detailed observations of CNe in X-rays, and with future missions systematic observations of galactic and extragalactic novae will be possible.

Introduction

CNe occur in accreting white dwarf plus main sequence binary systems, when accreted material ignites in a thermonuclear explosion. The explosion leads to the ejection of a mixture of material previously accreted and dredged up from the white dwarf. Super-Eddington luminosities then power a massive radiatively driven wind. The combination leads to significant mass loss (10^{-6} to 10^{-4} $M_\odot$ in a few weeks). The bolometric luminosity is assumed to be constant until nuclear burning ends but the spectrum undergoes dramatic changes, essentially walking through all wavelength bands from the optical to X-rays while coronal lines in the infrared appear throughout. Early in the outburst, the white dwarf is surrounded by an expanding shell of optically thick material that behaves like the stellar atmosphere of an F giant with the highest radiative output in optical light. When the ejecta become thinner, the photosphere recedes to inner and hotter layers, and the peak of the spectrum gradually shifts to higher energies until a bright supersoft X-ray spectrum with the shape of a blackbody of temperature $\sim 30\,\mathrm{eV}$ is observed. X-ray observations during this phase probe the innermost regions of the outburst. From high-resolution X-ray spectra we now know that these spectra have to be treated as extremely hot stellar atmospheres, however, appropriate atmosphere models for these extreme conditions are yet to be developed and refined. More accurate atomic data than presently available are needed for this purpose.

An important connection can be drawn from the similarity of these spectra with those of Super-Soft X-ray Sources (SSS) discovered as an extra class in the 1980s and interpreted as accreting white dwarfs with nuclear burning as their energy source. In novae, the appearance of a SSS spectrum is a transient phenomenon, while it seems to be a permanent state in the class of SSSs. Central nuclear burning as a permanent state is only possible if a steady supply of new burning material by continued accretion is available. Explosive nuclear burning as in CNe leads to mass loss which prevents the white dwarf growing in mass in spite of accretion. In contrast, steady nuclear burning as assumed to occur in the SSSs is less violent and the explosive nature of the accreted hydrogen-rich material is reduced by the conversion to helium. In this way a white dwarf could grow in mass and reach the Chandrasekhar limit. The SSSs are thus possible SN Ia progenitors. The occurrence of a phase of SSS emission in novae suggests a relationship, for example, some CNe may evolve into permanent SSSs, and both types of objects are worth studying.

Description of research program

Point of X-ray observations

With X-ray observations of CNe we see the deepest observable layers of the outburst where nuclear burning can *directly* be observed. In fact, oscillations that can be linked to nuclear burning have been found in X-ray observations of some novae, but not in all. Those regions observed in X-rays are predominantly controlled by the white dwarf and are the footpoint of the outflow. In the past I have made most use of *Swift*, *Chandra*, and *XMM-Newton*, which provide complementary information (see below). Future X-ray missions will be important for more complete surveys including also extragalactic novae (more below).

Observations at longer wavelengths yield insights into the outer layers and thus the dynamics and composition of the ejected material that escapes into space. A full profile of a CN outburst thus requires observations in all wavelength bands. I am collaborating with observers of novae in other bands, particularly in radio, infrared, and optical.

Challenges

Although the general principles of nova evolution are fairly well understood, all observed novae have behaved differently, and no proposed classification scheme is as yet comprehensive or fully predictive. We have found a number of unexpected behaviors, e.g., rebrightenings, sudden turn offs, flares, etc. which demand explanations that are difficult to fit in one standard picture. The situation is complicated by the fact that most novae are poorly observed in multiwavelengths, and for very few novae do we have systematic monitoring observations in X-rays.

With the high-resolution X-ray spectrometers provided by *Chandra* and *XMM-Newton* we are entering new territory, and we have to realize that the spectral models have to be a lot more complex than previously required. In Fig. 1 I illustrate the complexity of the problem. Atmosphere models computed with PHOENIX (P. Hauschildt, Hamburg) give encouraging reproduction of the rough shape of the continuum, but when looking in more detail, these models are unsatisfactory. Radiative transport is a complex process, and atmosphere models return highly structured spectra, even if the number of lines is relatively small. On this background accurate and complete atomic data are crucial, but at present the required quality of X-ray atomic databases is not available yet. In past spectroscopic analyzes atmosphere models have been used, but had to be smeared out to the poor spectral resolution of past instruments, and no serious refinement of model parameters was possible. I am working on concepts to explore the X-ray spectra to their limits. My knowledge from the X-ray spectra of Stellar Coronae will be helpful in this endeavor.

Approaches

The PHOENIX code is able to compute the radiative transport in the co-moving frame, which is more realistic towards the true conditions than static plane-parallel white dwarf atmosphere models like that shown in Fig. 1. We don't know what effects the inclusion of the dynamics will have, but features like the predicted edge at 16.7 Å may be smeared out, giving a better representation of the data. This project is in collaboration with Prof. P. Hauschildt (Hamburg) and his student D. v.Rossum. In addition to global atmosphere models it is important to study selected individual lines in detail. A first approach was introduced in my recent paper [4] and I am planning to refine this approach with a student from Munich, Ralph Schönrich, who want to do his Ph.D. project with me.

In order to approach a classification scheme with the aim to predict the evolution of an outburst based on a few fundamental properties (like white dwarf mass), we need more complete coverage in observations. At present a large fleet of radio and infrared instruments is pointing at all observable novae, and with *Swift* the same is happening in X-rays and UV (I am member of a Swift Nova group, headed by Dr. J.P. Osborne; Leicester, UK). Future proposed X-ray missions push for advances in sensitivity at higher energies, but most of them include soft X-ray instruments which allow observations of novae. Higher sensitivity and spectral resolution allow a larger fraction of novae to be observed in X-rays, and novae in other galaxies will also be observable. All three wavebands linked together

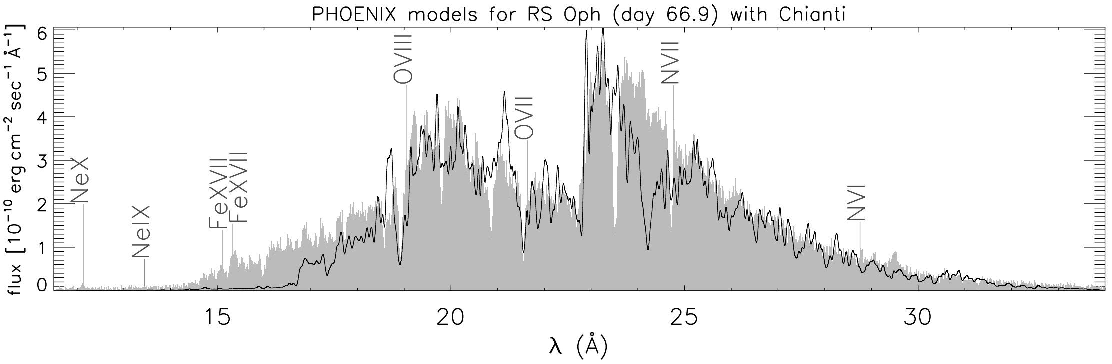

Figure 1: X-ray spectrum of the recurrent nova RS Oph during the SSS phase (grey shadings) with a preliminary stellar atmosphere model (black solid line) that assumes a static plane parallel white dwarf atmosphere in NLTE with solar abundances at an effective temperature of 6.5×10^5 K. We are planning more realistic dynamical models which account for the expansion. This may smear out edges like that at 16.7 Å (ionization of O VII), but adjustment of elemental abundances also yield significant changes.

yield the full profile of an outburst, from the center where nuclear burning occurs (observed in X-rays) to the outer layers where mass loss can be observed in infrared and radio.

Current and upcoming projects

The nova event of the year 2006 was the sixth recorded outburst of the recurrent nova RS Ophiuchi, which has been followed in X-rays with unprecedented coverage by *Swift*, *Chandra*, and *XMM-Newton*. The observations with *Swift* and *Chandra* plus *XMM-Newton* contain complementary information. With *Swift* we have the best temporal resolution of a nova event ever, and I am collaborating with Dr. J.P. Osborne (Leicester University) to analyze these data. The spectral resolution of *Swift*, however, is not high enough to sufficiently constrain atmosphere models, and we need support from the high-quality spectra obtained with *Chandra* and *XMM-Newton*. I plan to apply PHOENIX atmosphere models (as that shown in Fig. 1) to the *Chandra* and *XMM-Newton* spectra, and then interpolate the parameters in order to map the spectral evolution, constrained by the *Swift* data.

My recent published paper [4] focuses on the SSS phase, and I am currently writing a second paper on the spectral evolution of the shock that occurred between the nova ejecta and the stellar wind of the companion ([70]). These spectra are similar to those of Stellar Coronae, and I determined the temperature structure and the elemental composition. I am working in a team of observers and theorists, where my part is to analyze the high-resolution X-ray grating data, together with Dr. Jeremy Drake (Harvard University). The low-resolution *Swift* spectra of the shock are analyzed by Prof. M. Bode (Liverpool), and theoretical models are computed by Dr. T. O'Brien (Manchester). Observations in IR are analyzed by Prof. A. Evans (Keele) and Dr. C. Woodward (Minneapolis), while radio observations, e.g., with eMERLIN, will provide higher quality imaging that can be deeper or more frequent and place constraints on the progress of mass loss (Dr. S. Eyres, UCLan).

Other X-ray observations of CNe during different phases of their evolution are waiting to be analyzed. I recently published a sample of novae observed with *Swift* ([5]) which illustrates that all outbursts evolved differently and for each dataset one has to develop new approaches. I am currently finalizing a paper on the nova V723 Cas which exploded in August 1995, and was discovered by *Swift* to still be active in January 2006 ([67]). The long life time of this particular nova is challenging to understand, and a possible explanation is that accretion occurs at the same rate as nuclear burning. In that case the white dwarf is gaining mass and the nova will continue to be active until it explodes as a SN Ia.

Studies of Stellar Activity in X-rays and other wavelengths

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Abstract

Based on my past research in high-resolution X-ray spectroscopy of Stellar Coronae, I pursue continued research in this field, but not only in X-ray spectroscopy. Progress beyond high-resolution X-ray spectroscopy lies in multiwavelength studies that map all activity tracers observable in optical, UV, and X-rays. I am involved in a collaboration where we carry out strictly simultaneous observations with *XMM-Newton*+VLT, allowing us to construct a 3-dimensional map of a stellar corona. With the present instrumentation we are limited to fast rotators, but future instruments will allow us to assess slower rotators as well. Future X-ray instruments with increased sensitivity are well suited for our studies, and some of the proposed missions are planned with improved sensitivity at a spectral resolution that can compete with the X-ray gratings.

Along a second line I plan to expand computer MHD models of individual coronal features (originally designed for the solar corona) to construct a model of a stellar corona. These models then need to be constrained by the findings of the above observational studies. This is an ambitious aim, but I have already set myself up with competitive collaborators who consider 3-d coronal models possible in the near future.

Introduction

In contrast to the uniform solar surface (photosphere), the corona is highly non-uniform with loop-like structures, active regions, and coronal holes. The only irregular features on the surface, the sun spots, appear to be the sources of activity, places, where magnetic fields pierce through the surface and heat the upper atmosphere to millions of degrees, temperatures which can only be observed in X-rays. In stellar coronae the coronal structures cannot be resolved, but the influence from stellar parameters, e.g. rotation, can be studied systematically. Characteristics of Solar activity are Sun spots, the chromosphere (20,000 degrees, ionized emission lines in UV and optical light), and the Corona (1 Million degrees, X-ray emission, highly ionized emission lines).

While spatially resolved observations are only possible for the solar corona, the connection of coronal formation with stellar parameters cannot be determined from only one object. With investigations of Stellar Coronae we cover a large range of stellar parameters that can be studied in relation to the formation of coronae. For example, the relationship between stellar rotation and X-ray luminosity was discovered from samples of stellar coronae, and would have remained undiscovered with studies of the solar corona alone.

Description of research program

•*Point of X-ray observations*

X-ray observations of Stellar Coronae allow uncontaminated views of coronae around the stars. Stars without a corona (e.g., early A stars) are not detectable in X-rays, thus all X-rays originate from the corona. Further, the plasma conditions are favorable for the spectral analysis because the simplifications of collisional equilibrium and optically thin plasma are valid. Unfortunately, however, coronal plasma is not uniform, and no spatial resolution in X-rays is achievable. We can thus only speculate about the spatial distribution of coronal plasma, however, we have a start with the spatially resolved solar corona.

•*Point of Multiwavelength Studies*

Strictly simultaneous observations with *XMM-Newton*+VLT allow us to (1) construct Doppler Images of the surface, finding star spots, (2) follow the passage of prominences and determine their height above the stellar surface (3) study the X-ray and UV light curves and associate their correlation with the first two activity indicators. The combined picture gives us 3-dimensional images of stellar coronae, providing an important step for the comparison of stellar coronae with the solar corona.

•*Challenges*

(1) All stars can only be observed as point sources. The only way to resolve spatial information is in rare eclipsing binaries. For studies of stellar activity, however, spatial information is crucial because all activity phenomena are non-uniformly distributed.

(2) High-resolution X-ray spectra of stellar coronae are the only way to assess the conditions in the upper corona. Even with the simplifications of collisional equilibrium and optically thin plasma, the interpretion of the emission line spectra is not trivial. Powerfull software packages (e.g., xspec, isis), are designed to compute spectral models accounting for the calibration and our entire knowledge of atomic processes, assuming a temperature distribution and elemental abundances which, by means of iteration, can be determined from a measured spectrum. However, the atomic data are incomplete and not all atomic transitions are known with the same precision. Further, the inversion problem is by nature not uniquely solvable, such that a range of different models may yield the same degree of reproduction of the data.

•*Approaches*

(1) The only solution to spatially unresolved observations is spectroscopy. In order to resolve features on a stellar surface, high-resolution optical spectra can be used for line profile analyzes. For fast rotating stars (e.g., Speedy Mic), high-resolution optical spectra allow the construction of maps of stellar surfaces, where active regions and star spots can be identified. Irregularities on the surface lead to deformations of the profiles of photospheric absorption lines, and the reconstruction of surface structures from line profile analyzes is called Doppler Imaging. The chromospheric Ca II H+K lines are deformed by prominences absorbing their light when passing through the line of sight at greater heights. From the speed of their passage their height above the surface can be reconstructed. Simultaneous observations in X-rays allow us to find correlations between sun spots derived from Doppler Imaging and X-ray flares. Their height can be determined from the time they appear before (or after) an associated sun spot enters (or leaves) the visible side of the star.

At a later stage, computer MHD models of isolated solar coronal structures can be combined, yielding a model of a full stellar corona. If these models can be constrained by the above observations, it will be possible to study the heating mechanism of stellar coronae.

(2) In order to overcome the problem of incompleteness of the atomic data and their inhomogeneous distribution in quality, one has to study each emission line individually. In collaboration with Prof. C. Jordan (Oxford) I have developed powerful tools to select only the best-known lines, based on which the emission measure distribution (EMD) can be reconstructed. Once the EMD is known, the elemental abundances can be determined.

Current and upcoming projects

XMM-Newton provides simultaneous X-ray photometry and spectroscopy with UV photometry. I am involved in a project with Dr. U. Wolter and Prof. J.H.M.M Schmitt (Hamburg), where we have obtained simultaneous *XMM-Newton* and VLT plus UVES data of the fast rotator Speedy Mic. From the UVES spectra we can identify active regions which can then be associated with increases and decreases of the integrated X-ray brightness and UV intensity. This observing program yields the best coverage of all activity parameters at the same time, delivering a 3-dimensional picture of stellar coronae ([3]). We have submitted a proposal to carry out the same analysis for the fast rotator AB Dor. With future optical spectrometers improved spectral resolution and sensitivity will be available, and our studies can be extended to slower rotators. While no proposed future X-ray mission has been approved at this time, it is likely that at least one will be approved that carries instruments suitable for sensitive X-ray photometry, and likely also high-resolution spectroscopy at the wavelengths required for our study. The advertised emphasis lies on higher energies, however, e.g., extragalactic research at high redshifts will demand high sensitivity at softer X-ray energies in addition to > 10-keV observations. We may not, however, have instruments with simultaneous UV photometry.

The interpretation of highly resolved X-ray spectra of Stellar Coronae is challenging in the way that a compromise has to be found between using only the best atomic data and using as much information as possible. In collaboration with Prof. Dame Carole Jordan (Oxford) I have reconstructed the coronal temperature distribution of the single star ϵ Eridani ([2]) and determined the elemental abundances. We carefully inspected every single emission line with the respective atomic data and line flux measurement. We finally selected 27 lines formed at different temperatures in order to find the mean emission measure distribution (EMD) and to adjust the elemental abundances. We also computed a theoretical emission measure distribution based on considerations of an energy balance between heating and radiative losses, which, compared to the measured EMD, gives us area filling factors.

As a first approach to use models of solar coronal structures to describe stellar coronae, a distribution of individual loops can be combined to form a model of a stellar corona. I have contacted Dr. Hardi Peter (KIS Freiburg), and we have started a project with his student Pia Zacharias ([69]). We first postulated a distribution of heating rates and loop lengths which result in a distribution of temperatures and densities. We then constructed a disk-integrated X-ray spectrum from these distributions as *Chandra* or *XMM-Newton* would measure it. We were able to recover the peak of the temperature distribution from the synthetic spectrum and made interesting discoveries how to measure a representative value of the density. [69] is only the start of a series of papers with the aim to test increasingly complex models.

The analysis of my latest *Chandra* observation of the M dwarf binary EQ Peg is under way, carried out by the student C. Liefke (Hamburg, [68]). We have obtained separate grating spectra of each component, and we can compare the coronal abundances of the two components. Since the stars are coeval, their photospheric abundances should be the same. We further compared each component with the X-ray spectra of other M dwarfs and found surprising resemblances and differences. We also detected a flare on one component and can follow the evolution of temperature, density, and abundances.