X-rays from A stars - Coronae and wind-shocks

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Abstract The X-ray properties of A stars are reviewed and their X-ray generating mechanisms discussed. A-type stars bridge the regimes of cool and hot stars and they exhibit diverse high-energy phenomena; notably, among A stars we find the hottest magnetically active stars as well as the coolest wind-shock stars. In the domain of late A-type stars the X-ray emission is related to the presence of coronae, while in Ap/Bp stars the magnetically channeled wind-shock model is applicable.

1. Introduction

Stellar X-ray emission from main-sequence stars separates basically in two fundamentally different groups, the cool and the hot star regime. A detailed review on stellar X-ray emission is given in [4].

In cool stars, i.e. stars of spectral types late A to late M, the X-ray emission is related to magnetic activity. Their magnetic fields are created by dynamo processes in the stellar interior that base on an interplay of outer convective motion and differential rotation. The X-rays originate from hot plasma ($T \gtrsim 1$ MK) in the outer atmospheric layer known as corona. Coronal X-ray emission is a well studied phenomenon and with the solar case a nearly example is available that allows the study of spatially resolved surface structures. X-ray emission from cool stars is a universal phenomenon, but their activity levels differ by several orders of magnitude $\log L_{\rm X}/L_{\rm bol} \approx -3 \ldots -7$ [15]. It turned out that in comparison the 4.6 Gyr old Sun is a rather inactive star. The X-ray luminosity of magnetically active stars is proportional to the dynamo power, which is often parameterized by the dimensionless Rossby-Number ($\mathrm{Ro} = P/\tau_c$) with P being the rotation period and τ_c the convective turnover time. The Rossby-Number depends on stellar rotation and due to spin down cool stars show a strong evolution of activity during their main-sequence lifetime.

In hot stars of spectral type O and early B, the X-rays originate from shocks in the fast and strong radiation driven stellar winds. Their X-ray luminosity scales basically with the bolometric luminosity and one finds $\log L_{\rm X}/L_{\rm bol} \approx -7$. The presence of scatter in the $\log L_{\rm X}/L_{\rm bol}$ relation particularly at higher X-ray energies points to the existence of secondary parameters, e.g. the presence of magnetic fields (see Nazé, this proceeding).

As a consequence one expects an X-ray 'dark zone' from mid B to mid A stars, since these stars have no outer convection zone and their winds are too weak to power X-ray emission. However, X-ray detections were reported at a fraction of about 10 % in RASS data, see e.g. [16]. The classical explanation for this finding is the presence of 'hidden' low-mass companions and since the stellar lifetime of mid B to mid A stars is with roughly $10^8 - 10^9$ yr rather short, their companions are expected to be quite active stars. This scenario is likely true for normal main-sequence stars as deduced from the high binary fraction for X-ray detected sample in optical follow-up campaigns like the VAST survey [3] and apparent X-ray properties that are reminiscent of active low-mass stars. Nevertheless, beside the pre main-sequence HAeBe stars not discussed here, intrinsic X-ray emission has been proposed to a specific sub-class of these stars stars, the Ap/Bp stars.

The Ap/Bp stars are magnetic, chemically peculiar stars. They have large-scale magnetic structures that are fundamentally different from the small-scale, entangled magnetic field that is underlying stellar coronae in cool stars. The magnetic field of Ap/Bp are rather simple and often dominated by a dipole, albeit higher multipole components are clearly detected in many objects. Their fields are likely of fossil origin (see Alecian, this proceeding) and can reach remarkable field strengths of up to many kG For Ap/Bp stars [1] proposed that their X-ray emission originates from a combination of magnetic field and stellar wind via a new mechanism, the so-called magnetically confined wind-shock (MCWS) model discussed below in more detail (see also ud-Doula, this proceeding).

The review will focus on more recent results obtained from *Chandra* and *XMM-Newton* observations and discuss similarities and differences of the X-ray emission in the various types of A stars. The first part will address coronal X-ray emission from 'normal' A stars, while the second part will deal with the magnetic Ap/Bp stars.

2. X-rays from 'normal' A stars

X-ray emission from late A stars has already been observed with *Einstein* and *ROSAT* in the 1980's and 1990's [14, 15], showing that these stars are faint and soft X-ray emitter. Their X-rays are interpreted as coronal

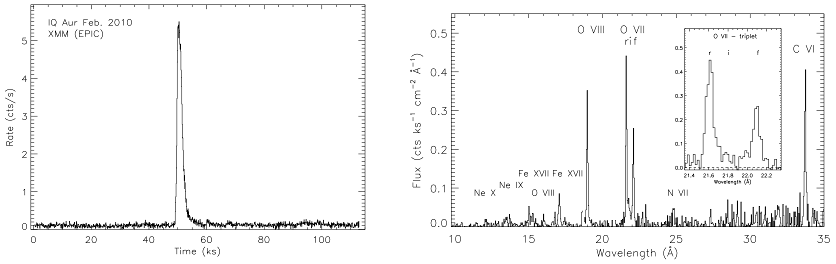

Figure 1. *left*: X-ray light curve of Altair; *right*: High-resolution X-ray spectrum, RGS data (from [11]).

emission, in the 'classical' picture they are generated by a weak dynamo operating in the thin outer convective layer of these stars.

The closest late-A type star is Altair (α Aql), making it the best candidate for in-depth X-ray studies. Altair is a single A7 IV-V star at a distance of only 5.1 pc; it has $T_{\rm eff} \approx 7800$ K and is with an estimated age of about 1.2 Gyr a moderately evolved main-sequence star. Altair is a very fast rotator with $V sini \approx 220$ km s^{-1}, but fast rotation is typical for these objects. Many magnetic activity indicators have been observed from Altair, ranging from Lyα (*IUE*) over OVI (*FUSE*) [10] to X-ray emission, respectively characteristics of chromospheric, transition region and coronal emission. A deep *XMM-Newton* observation was performed to study its X-ray properties with modern instruments [11].

The *XMM-Newton* observation detected Altair as an X-ray source with $L_{\rm X} = 1.4 \times 10^{27}$ erg s^{-1}, similar to the *ROSAT* value. Theses measurements show that a long-term stable corona is present on Altair, although the X-ray light curve shown in Fig 1 exhibits moderate variability on short timescales from minor magnetic activity and rotational modulation. The new observations allowed to determine the coronal properties of Altair in greater detain and it was found that they resemble those of the inactive Sun, despite quite different underlying stars. The corona of Altair is dominated by cool $1-4$ MK plasma and shows solar-like elemental abundances, e.g. FIP effect, Ne/O ratio etc. Another remarkable feature is the shift of the X-ray saturation limit. The activity of solar-like stars saturates at $\log L_{\rm X}/L_{\rm bol} \approx -3$, while the corresponding activity level of Altair is with $\log L_{\rm X}/L_{\rm bol} = -7.4$, more than four orders of magnitudes lower. Since Altair is a very fast rotator that is rotating with $\gtrsim 60\%$ breakup-speed, a significant spin up would destroy the star. Therefore the saturation limit is apparently reduced for late A stars by several orders of magnitude.

Another effect of Altair's fast rotation is that it not a sphere as shown by interferometric measurements made by the CHARA array [9]. The star is oblate with an axial ratio of $\mathrm{a}\,/\,\mathrm{b} \approx 1.1 - 1.2$ and shows strong gravity darkening, i.e. it does not have a homogeneous surface temperature but rather a not necessarily perfectly azimuthally symmetric temperature distribution ranging from $T_{\mathrm{eff}} = 6900$ K at the equator up to 8500 K at the poles. Combining this finding with the analysis of UV-sensitive OVII X-ray lines ratios indicate that coronal structures located on the stellar surface require $T_{\mathrm{eff}} \lesssim 7400$ K. Therefore the corona is not uniformly or randomly distributed over the star as expected in the shallow convection zone model, but rather has to be located a low latitudes around the cooler equatorial bulge. Therefore this phenomenon was named 'equatorial bulge corona' [11].

While Altair is the best studied case, it is not an outlier and very similar X-ray properties were found for the A7 star Alderamin. In contrast, no significant magnetic activity is found at spectral types earlier than A5 and deep X-ray observations obtained tight upper limits on Fomalhaut (A3) and Vega (A0) [15].

Nevertheless, some minor and possibly residual activity might be present in younger mid A stars. An example is β Pictoris, an A5 star at an age of about 10 Myr that is famous for its massive debris disk was detected as a very faint and extremely soft X-ray source by *XMM-Newton* [6]. In these data an excess is seen around OVII emission lines, later the detection was confirmed by a *Chandra* HRI observation [5]. While the super-rotationally broadened OVI lines seen by the *FUSE* satellite seem to indicate some kind of boundary layer scenario, a faint corona $L_{\mathrm{X}} \lesssim 10^{26}$ erg s^{-1} with temperatures of ~ 1 MK is favored in the analysis that included the new X-ray data from *Chandra*.

However, other claims of bright X-ray emission from earlier A stars have turned out to be a result of a 'misclassification'. An example is the planet hosting star HR 8799, often classified as A5 star. X-ray observations clearly detect this star at $L_{\mathrm{X}} = 1.3 \times 10^{28}$ erg s^{-1}, $\log L_{\mathrm{X}}/L_{\mathrm{bol}} \approx -6.2$ with coronal temperatures of $T_{\mathrm{X}} \approx 3$ MK [12]. Inspecting literature, one finds that HR 8799 is a kA5hF0mA5 v λ Boo star. This means that the A5 classification is based on metal lines, while hydrogen lines give spectral type F0, consistent with its low $T_{\mathrm{eff}} \approx 7450$ K. Consequently, from an activity point of view HR 8799 is rather a very late A or even early F star, fully consistent with the X-ray measurements.

3. X-rays from Ap/Bp stars

The Ap/Bp stars are chemically peculiar, magnetic stars where the large-scale magnetic structures open another possible mechanism for the generation of energetic radiation, including X-rays. The X-ray detection of the A0p star IQ Aur with *ROSAT* as a bright but soft X-ray source with $\log L_{\rm X} = 29.6$ erg s^{-1} and $T_{\rm X} = 0.3$ keV (3.5 MK) lead to the development of the magnetically confined wind-shock (MCWS) model [1]. In the MCWS scenario the radiatively driven wind components from both stellar hemispheres are magnetically channelled and forced to collide in the vicinity of its equatorial plane where strong shocks produce X-ray emission. With the kinetic wind energy being the main energy source, mainly the mass loss rate and the wind speed determine the X-ray properties of the these stars. Assuming a 4 kG dipole and a high efficiency of the MCWS-mechanism, the X-ray properties require reasonable parameter of $V_\infty = 800$ km s^{-1} and $\dot{M} \approx 10^{-10...-11}\ M_\odot\,{\rm yr}^{-1}$ as shown in [1].

Advancements of the MCWS model are described in a series of paper by ud-Doula, Owocki and Townsend, which use MHD/RFHD simulations to obtain dynamic models, include stellar rotation etc., see e.g. [18, 17, 19]. Of major importance in characterizing the magnetosphere of hot stars is the dimensionless parameter η_* that was introduced by [18] to describe the degree of magnetic confinement, basically the ratio of magnetic field to kinetic wind energy density. It was shown that for strong confinement, i.e. large values of η_*, a corotating rigid disk structure is formed around the stars. The disk shows a complex dynamic behavior with matter infall and centrifugal breakout events occurring controlling the mass of the disk. For the here considered Ap/Bp stars η_* is very large, i.e. the conditions for strong confinement are always fulfilled.

The MCWS scenario became the 'standard' model for magnetic hot stars and was invoked to explain e.g. X-ray overluminosities, hard spectral components, flares, rotational modulation of stellar X-ray emission. The model was mainly used to describe O and B-type stars and successfully applied in several cases, but it failed partially in other stars. Here future developments like full 3D MHD simulations might provide additional insights.

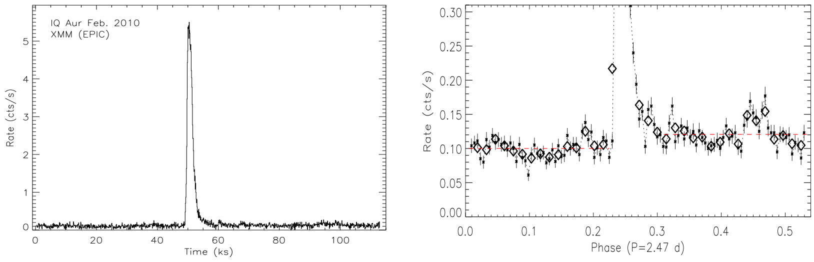

Figure 2. X-ray light curve of IQ Aur, *left*: EPIC data, 0.2-8.0 keV, *right*: quasi-quiescent X-ray emission with different temporal binning and phased with the rotation period (from [13]).

IQ Aur is with $\mathrm{B-V}=-0.16$, $T_{\mathrm{eff}} \approx 14500$ K, $M = 4.0\,M_{\odot}$ among the hottest and most massive A0p stars and the star was re-examinated in X-rays in a deep *XMM-Newton* observation [13]. The X-ray lightcurve shown in Fig. 2 brought surprises like a large flare, on the other hand the observation confirmed basic X-ray properties like the quasi-quiescence X-ray luminosity of $\log L_{\mathrm{X}} = 29.6$ erg s^{-1} ($\log L_{\mathrm{X}}/L_{\mathrm{bol}} \approx -6.5$), proving that the X-ray emission of IQ Aur is quite stable over decades. In addition the new X-ray data added many details and new findings. Utilizing high-resolution X-ray spectroscopy and emission line ratios from OVII it was shown that the X-ray emission originates from well above the stellar surface at distances of several stellar radii (d $\gtrsim$ 7 R_{*}). The *XMM-Newton* observation allowed to study short-term X-ray brightness changes. Beside some minor variability of the quasi-quiescent state, the X-ray light curve shows that a clear rotational modulation is not present (see right panel of Fig. 2, constraining any viewing angle dependence of the emitting plasma. Further IQ Aur shows an excess of cool plasma as traced by the OVIII/OVII line flux ratio compared to coronal stars, indicating that non-magnetic processes are responsible for or at least contributing to the X-ray production. These findings are in overall agreement with the predictions from the standard MCWS model.

However, the *XMM-Newton* spectrum exhibits the presence of a strong hot ($\gtrsim$ 10 MK) plasma component, beside the cooler emission already detected by *ROSAT*, in the quasi-quiescence state of IQ Aur. While this is already hardly explainable within the wind-shock scenario for the stellar properties of IQ Aur, the observation of a strong X-ray flare clearly points to the presence of some kind of magnetic activity phenomenon. The large flare produces a flux increase of a factor ~ 100 and is accompanied by very hard X-ray emission. At the peak of the event the X-ray brightness reaches $L_{\rm Xpeak} = 3 \times 10^{31}$ erg s^{-1} and we find very hot plasma with temperatures of $T_{\rm X} \lesssim 100$ MK and a metallicity increase in the X-ray emitting plasma. This behavior is rather typical for flares observed on coronal sources and its fast rise and total duration 2 h already point to a rather compact event. An analysis gives $L \lesssim 0.2\, R_*$ for the size of the emitting structure, indicating a small, localized region within the star-magnetosphere system as origin of the energy outburst.

How can these findings for an Ap star be interpreted? The derived X-ray properties favor a scenario where X-rays are generated by wind-shocks and magnetic activity. The X-ray emission likely originates in a wind-shock region at least several stellar radii away from the stellar surface, including a disk-like structure. The flare requires magnetic activity already on temperature arguments and derived sizes rules out an event in the large dipolar magnetic structure of the star. A possible location would be a segment of the rigid rotating disk around IQ Aur, where magnetic reconfiguration of break-out has occurred. As a caveat there remains the possibility of an unknown companion to IQ Aur. Albeit no hints exists on binarity, it cannot be ruled out completely by the existing data. To approach this possible problem, is it instructive to investigate a larger sample of similar objects.

Several other Ap/Bp stars have been studied in X-rays and combining new X-ray observations with archival data brought up new findings on the X-ray emission of these objects as a class. At maximum contrast to IQ Aur is the *Chandra* ACIS observation of α^2 Canum Venanticorum [13], another prototypical A0p star. The star was not detected at $\log L_{\rm X} < 26$ erg s^{-1}, suggesting that optically similar stars differ in X-ray luminosity by factor $\gtrsim 1000$. But how similar are A0p stars? Studies by other authors focussed e.g. on hot stars with magnetic fields [2] and also the literature shows a puzzling zoo of detections and non-detection in the regime of Ap/Bp stars. To investigate the X-ray emission of these objects as a class and to obtain a larger sample of suitable, i.e. likely single or resolved Ap/Bp stars around spectral type A0, we initiated further X-ray observations with *XMM-Newton* and *Chandra* and searched their archives for suitable

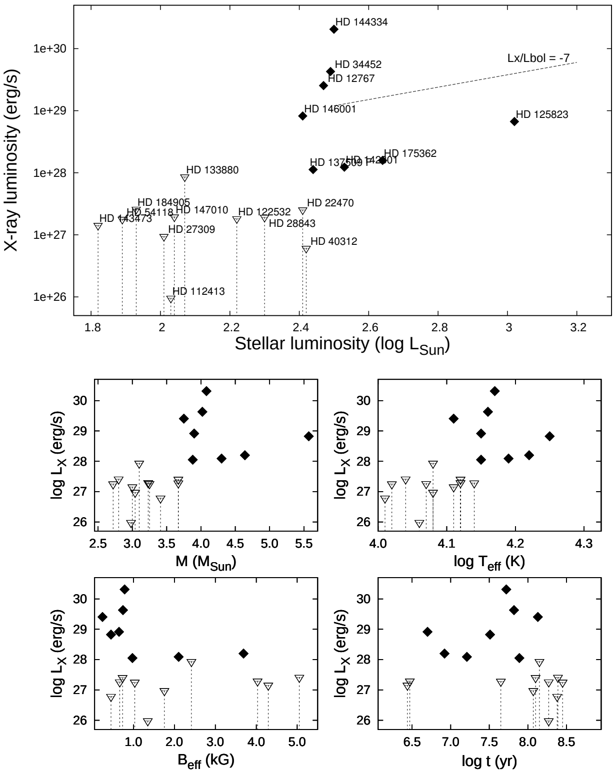

Figure 3. X-ray luminosity of Ap/Bp stars vs. bolometric luminosity (*top*) and other stellar parameter (*bottom*); updated versions from [13]. X-ray detected stars are plotted as diamonds, U.L.s as downward triangle.

targets. Beside enlarging the sample size our dedicated observing program aims to fill in data gaps in stellar parameter space. The investigated stars are late Bp to early Ap stars, all stars are rather well characterized, the here used stellar data is taken from [7].

So far about 20 stars have useful X-ray data, a nearly 50% increase compared to to the sample in [13], and as shown in Fig. 3 roughly half of it turned out to be X-ray emitter. Several trends emerge from the analysis of the extended data set, mainly strengthening the conclusions from [13]. First and most striking only optically brighter stars are X-ray detected ($L \gtrsim 200 L_{\odot}$). In contrast so far none of the fainter stars is detected as an X-ray source. Second, we find a large scatter in X-ray luminosity by up to two orders of magnitude for stars with similar optical luminosity. In the bottom panel we compare X-ray luminosity to other stellar parameter, here mass, effective temperature, magnetic field strength and age. A similar division/relation as above is obtained when comparing X-ray luminosity to stellar mass or effective temperature, obviously related parameter to luminosity. On the other hand, age or magnetic field strength apparently play at best a minor role in making an Ap/Bp star an X-ray source.

The finding that predominantly the more luminous Ap/Bp stars are X-ray sources clearly favors an intrinsic X-ray generation mechanism in contrast to binary scenario, where no such correlation or dependence on stellar parameter is expected. This dependence is physically reasonable, since more luminous and hotter stars are expected to drive stronger and faster winds. Another support for intrinsic emission emerges when comparing the X-ray to the radio data of Ap/Bp stars [8]. Companions would be coronal sources that follow a rather tight correlation between radio and X-ray luminosity, the so-called Güdel-Benz relation, but one finds that the Ap/Bp stars are radio-overluminous by orders of magnitudes. This finding provides further evidence of intrinsic, non-coronal emission and the violation of the correlation make late-type stars an unlikely source of the detected emission.

However, several open issues remain, most obvious the scatter in $L_{\rm X}$ and the apparently very sharp transition between X-ray bright and X-ray dark (or very faint) sources. Possible explanations for the scatter in $L_{\rm X}$ are e.g. influence of magnetic field topology and viewing geometry, time variability or the presence of an occasional companion. The quite sharp transition remains unexplained, suggesting that a kind of threshold mechanism is operating. Probably an interplay between several parameters shape the final X-ray appearance of Ap/Bp stars. Future studies of key objects and larger samples will address these issues.

Overall, the MCWS mechanism provides a useful scenario to explain the X-ray emission of Ap/Bp stars as a class. Here the more massive, brighter and hotter Ap/Bp stars have a sufficient mass loss and wind speed that lead in combination with a strong magnetic confinement to the observed X-ray phenomena.

4. Summary

The X-ray phenomena of A stars are very diverse and fundamentally different between late A stars and Ap stars. X-ray emission from magnetic activity is clearly detected in 'normal' late A stars. The nearby single star Altair is a well studied example and its X-ray properties resemble those of the quiescent sun, despite very different underlying stars. The late A stars are overall weakly active and their coronae are dominated by relatively cool plasma at temperatures of 1 –3 MK. Magnetic activity could become localized phenomena, most prominent in the cooler equatorial bulge regions. While early to mid A stars are virtually X-ray dark, minor and/or residual, magnetic activity is seen at mid A spectral types in young objects.

In magnetic main-sequence stars, the chemically peculiar Ap/Bp stars, the detected X-ray emission can be described by a magnetically channeled stellar wind models. The X-ray emission of Ap/Bp stars can be attributed to wind-shocks, additionally a contribution from activity in a rigid disk that is formed out of accumulated wind material might be present. X-rays are detected predominantly from the more luminous, more massive, hotter stars, but secondary parameter need to be investigated and many details are still open.

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