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Letter to the Editor

A BeppoSAX observation of the coronal X-ray emission of the active binary VY Ari

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Abstract. We present a study of the X-ray coronal emission from the active binary VY Ari, using data from both the Low Energy Concentrator Spectrometer (LECS) and the Medium Energy Concentrator Spectrometer (MECS) instruments on-board the X-ray satellite BeppoSAX. Using these instruments, the X-ray spectrum of VY Ari can be studied across two full decades of energy, from 0.1 to 10 keV. The spectrum is well fit, across the whole spectral range, with an optically thin plasma MEKAL model with two discrete temperature components, and with an inferred coronal abundance [Fe/H] $\simeq -0.4$, corresponding to the average typical value of the photospheric abundance in RS CVn-type binaries.

Key words: Stars: individual: VY Ari; stars: late-type; stars: activity; X-rays: stars

1. Introduction

Late-type stars in tidally-locked binaries have long since been shown to be strong coronal X-ray emitters, with much higher X-ray luminosities than observed in otherwise similar single stars, reaching values of up to $\simeq 2 \times 10^{31}\,\mathrm{erg\,s^{-1}}$. This strong enhancement of the coronal activity has been observed across a wide range of ages and evolutionary statuses for the components of tidally locked systems, including Pop. I main-sequence and evolved stars as well as Pop II stars. Given the well-demonstrated strong dependence of coronal X-ray emission on stellar rotation (most likely through a dynamo mechanism), the enhanced X-ray emission of tidally-locked binaries with respect to single stars of the same mass and evolutionary stage can be mostly explained through their high rotational velocity, induced by the tidal locking mechanism itself. These systems thus constitute the ideal testbed for studying the phenomena of stellar activity at rather extreme levels, which are rarely reached in single stars except during their youngest evolutionary stages, when the star is still spinning rapidly due to its residual "fossil" angular momentum.

Given their high X-ray luminosities, tidally-locked binaries have been among the first stellar X-ray sources observed, and among the best studied to date. The thermal nature of their X-ray emission was shown using large samples by the *Einstein* Imaging Proportional Counter (IPC) observations, and, at the limited spectral resolution of the IPC detector, most observations are compatible with a simple thermal structure, modeled through the presence of just one or two plasma temperature components (e.g. Schmitt et al. 1990). More active stellar coronae appear, as a trend, to have higher plasma temperatures than less active ones, and tidally locked binaries obey this rule, so that their coronal temperatures are generally higher than those of single stars, with values of up to a few times 10^7 K for the hot component, and a few times 10^6 K for the cool component. A similar picture of coronal emission from tidally-locked binaries emerges from the observations of the ROSAT All Sky Survey (RASS), with most ROSAT PSPC spectra also being satisfactorily fit with two isothermal components (Dempsey et al. 1993).

When considered as a class, tidally-locked binaries show some unexpected peculiarities. Their photospheric metal abundance appears to be lower than the solar value, with RS CVn-type systems showing a typical range of [Fe/H] comprised between $\simeq -0.8$ and $\simeq -0.2$, or, equivalently, between $\simeq 0.15$ and $\simeq 0.6$ times the solar metallicity (Randich et al. 1993; Randich et al. 1994). It is still unclear what the causes of this widespread photospheric metal under-abundance are. Tidally locked systems have been variously classified, with often overlapping classifications (see Favata et al. 1995 for a discussion), depending for example on the rotational period or on the evolutionary status of the components. Indeed, it is unclear whether they can be considered together as a class with homogeneous

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characteristics, or whether the phenomenological definition of tidally-locked binary will not group together systems of widely different characteristics, origins, and evolutionary status.

Thanks to their high X-ray flux, tidally-locked binaries have also been an obvious target for the higher-spectral resolution CCD detectors of the ASCA Solid State Spectrometer (SIS) instruments. The SIS spectra of many coronal systems require a plasma of sub-solar metallicity to be satisfactorily fit (White 1996), and this has in some cases been considered as an indication of the presence of different metal abundances in the corona with respect to the photosphere, prompting a debate about the eventual reality of a so-called "Metal Abundance Deficiency" syndrome (or, in brief, "MAD" syndrome, Schmitt et al. 1996). However, the case for coronal under-abundances has often been discussed on the basis of comparison with the somewhat arbitrary solar abundance values, with the (more relevant) issue of the relationship between coronal and actual photospheric abundance having been less thoroughly investigated. Indeed, many active binaries show lower-than-solar abundance values both in their photosphere and in their corona, as for example CF Tuc (Schmitt et al. 1996) or λ And (Ortolani et al. 1997), although for some single, active stars (i.e. AB Dor, Mewe et al. 1996) the ASCA- and EUVE-derived coronal abundance appears to indeed be lower than photospheric. The first results on coronal emission from the BeppoSAX LECS detector for both Capella (Favata et al. 1997c) and β Cet (Maggio et al. 1997) show no evidence for sizable coronal under-abundances with respect to photospheric values. Many SIS spectra can still be fit with two discrete temperature components; some of the higher signal-to-noise spectra do not however yield a satisfactory reduced χ^2 when fit with such simple models (White 1996, Drake et al. 1996), independently from the assumed coronal abundance. This hints at more complex temperature structure possibly being present in their corona, or at problems in the plasma emission codes or in the detector calibration.

The X-ray satellite BeppoSAX (Boella et al. 1997a) includes four co-aligned Narrow Field Instruments, of which two sets are of relevance here: the Low Energy Concentrator Spectrometer (LECS, Parmar et al. 1997), and the three Medium Energy Concentrator Spectrometers (MECS, Boella et al. 1997b). The LECS and MECS have imaging capabilities and cover the energy band 0.1–10 keV and 1.7–10 keV respectively.

The LECS characteristics make it specially suited for the study of stellar coronal emission. Its resolution is comparable to the resolution of CCD detectors at low energies, and it offers access to the spectral region below $\simeq$ 0.5 keV, where typical coronal sources emit the largest photon flux. The region below the carbon edge is specially important as it provides the only essentially line-free region accessible with a large photon flux in a coronal source. In addition, the three MECS units provide in the overlapping band an effective area about three times the one of the LECS alone, with similar energy and spatial resolution. The larger effective area obtained by combining the LECS and MECS data at higher energies allows for example to more effectively study the Fe K complex at $\simeq$ 6.7 keV, a useful diagnostic both of coronal abundance and of temperature structure in the harder coronal sources. The unprecedented wide spectral coverage and good spectral resolution, in particular at the low energies, of the LECS detector, makes it an effective diagnostic tool for the determination of global coronal abundance, with its broad band more than offsetting the lower spectral resolution in comparison with the SIS CCD detectors (Favata et al. 1997b). The generally lower spectral resolution of the LECS detector with regard to CCD detectors, however, makes it much less efficient for the determination of the abundance of individual elements.

Among the sources included in the Science Verification Phase (SVP) of the BeppoSAX mission, VY Ari was included as a "prototype" coronal source. VY Ari (HD 17433) is a bright (V = 6.9), nearby (d = 21 pc), non-eclipsing SB1 binary system, in which the visible star is classified as K3–4/V–IV (Bopp et al. 1989), with a so-far unobserved lower mass companion, which is estimated, on the basis of the mass function of the system, to be a dM star. The binary orbit is nearly circular (e = 0.085), with an orbital period of 13.2 d. The photometrically derived rotation period of the primary is 16.4 d. The photospheric lithium abundance (Bopp et al. 1989), at N(Li) $\simeq$ 1.0, is typical for active binaries (Randich et al. 1993), and the surface gravity of the primary appears consistent with its being slightly evolved. No determination of its photospheric metal abundance is available in the literature.

VY Ari has been observed before in the X-rays by the *Einstein* IPC detector and by the ROSAT PSPC detector, both during the ROSAT All Sky Survey (RASS) and in pointed mode. It has not however so far been observed by the ASCA satellite. Both the IPC (Schmitt et al. 1990) and PSPC-RASS (Dempsey et al. 1993) data sets were fit with two-temperature Raymond-Smith optically-thin plasma models, and yielded best-fit temperatures of 0.22 and 1.55 keV (IPC) and 0.18 and 1.38 keV (PSPC), with a ratio between the emission measures of the soft and hard component of 0.051 and 0.28, respectively. The derived X-ray luminosities were 1.25×10^{30} and 2.34×10^{30} erg s^{-1}. No analysis of the ROSAT pointed data (which were taken with the boron filter in place) has been published thus far.

2. Observations and data reduction

The BeppoSAX SVP observation of VY Ari took place on September 4–6, 1996, resulting in 37 ks of observing time in the LECS detector and in 88 ks of observing time in the MECS detectors, the difference being due to the LECS being operated only during Earth night at the time of observation. All the instruments performed nominally during the observation, and there was no flaring activity, although an increase in the X-ray count rate during the last BeppoSAX orbit of the observation suggests the possible on-set of a flare. The number of photons detected in the last orbit is however too small to allow for time-resolved spectroscopy to be performed.

The LECS data were reduced through the standard LECS pipeline software (SAX-LEDAS 1.4.0), which produces a cleaned, linearized photon list, with energies expressed in pulse-invariant (PI) channels and event coordinates in RA and Dec.

The default screening criteria defined in the LEDAS system were applied, and inspection of the light curve for both the source and the local background showed that no additional screening was necessary. The MECS data were reduced using the XAS V. 2.0.1 package. The reduction was performed separately for each unit, again following the default screening criteria. The source spectra were extracted from a circle centered on the source itself of radius 8 arcmin and 4 arcmin respectively for the LECS and the MECS. The extraction of the LECS spectrum and of the background spectra was performed using the XSELECT package, and the spectral analysis using the XSPEC V. 9.0 package. Publicly available matrices (known as "Dec. 31, 1996" version) were used for the MECS, while the LECS response matrix was computed with the LEMAT package (V. 3.2.0). To subtract the background standard background files obtained by adding up a set of "empty sky" observations were used, extracted from the same circular region as the source spectra. The source spectra were re-binned so to have at least 20 counts per re-binned channel, and channels with energies between 0.1 and 9.0 keV and between 1.7 and 9.0 keV were retained for the LECS and MECS detector respectively. The resulting (background-subtracted) source count rate is 0.28 cts s^{-1}, with a background count rate, for the same region, of 0.05 cts s^{-1} for the LECS, and 0.20 cts s^{-1}, with a background count rate of 0.008 cts s^{-1} for the set of three MECS detectors taken together.

3. Results

The resulting spectra from the LECS and from the MECS detectors were simultaneously fit with an optically-thin plasma emission model with two discrete temperature components and freely varying global metal abundance. The MEKAL plasma emission model (Mewe et al. 1995) was used throughout, as implemented in XSPEC 9.0. The effect of interstellar absorption was included, by adding a WABS multiplicative component to the spectral model (implementing the Morrison & McCammon 1983 interstellar absorption model). Given the current uncertainties on the absolute calibration of the various detectors, the relative normalization of each MECS detector with respect to the LECS has been left as an additional free parameter in the fit. The fit converges to a relative normalization of the MECS detectors $\simeq$ 30% higher than the LECS, in line with the expected calibration uncertainties at this stage. Due to the longer exposure time, as well as to the larger effective area, the MECS spectra allow a much better constraint to be placed on the flux from Fe K complex. Detection of the Fe K complex supplies a diagnostic of the metallicity of the emitting plasma which is independent from the main diagnostic available to LECS spectra, i.e. the balance between the essentially line-free low-energy continuum (below the carbon edge) and the line-rich region around 1 keV, mostly due to the Fe L line complex.

The resulting best-fit model is shown, together with the observed spectrum and the fit residuals, in Fig. 1. The fit has a reduced χ^2 of 1.09 (with 523 degrees of freedom). The best-fit temperatures are 0.85 ± 0.04 and 2.1 ± 0.08 keV, with a ratio between the two emission measures (soft/hard) of 0.44. The

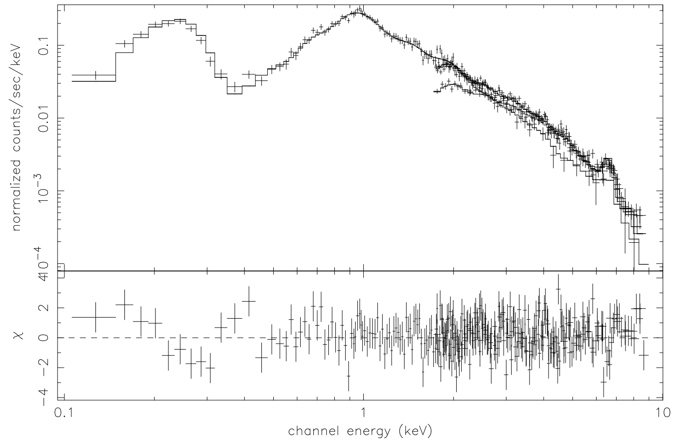

Fig. 1. The observed BeppoSAX LECS and MECS (for $E \geq 1.7$ keV) spectrum of VY Ari, together with the best-fit two-temperature MEKAL model spectrum. To reduce visual clutter the data have been re-binned, in the plot, by an additional factor of two with respect to the binning scheme used for the fit

best-fit metal abundance is 0.37 ± 0.04 times the solar value (corresponding to [Fe/H] $\simeq -0.4$), and the best-fit implied hydrogen column density is $(4.3 \pm 0.9) \times 10^{19}$ cm^{-2}.

Published values for the column density toward VY Ari are somewhat inconsistent. Fruscione et al. (1991) report on column density measurements toward the star ρ Ari, which is close to VY Ari (at a projected distance of 14 deg in the sky) and at a similar distance (25 pc) Based on the column density of Na I, these data yield an upper limit to the value of N(H) of 1.2×10^{19} cm^{-2}. Another upper limit to the column density of 2.0×10^{19} cm^{-2} has been derived by Diamond et al. (1995) for a distance of 20 pc in the sky direction of VY Ari, based on the observation of ROSAT EUV Wide Field Camera sources. A value of 2.2×10^{19} cm^{-2} is obtained by Dempsey et al. (1993) from a spectral fit to the RASS data. Dupree et al. (1996) quote a much lower value of 1.0×10^{18} cm^{-2}, derived from an analysis of the EUVE spectrum.

The LECS-derived best-fit value for the column density appears to be on the high side with respect to previously derived values, which are however not fully consistent with each other. Given the nature of the LECS spectral response, source metallicity and interstellar absorption are not wholly uncorrelated, with a low metallicity spectrum potentially mimicking the effects of high interstellar absorption. To assess the possible influence of such an effect we repeated the fit fixing the interstellar absorption at 1.0×10^{19} cm^{-2}, a value significantly lower than the best-fit one, but more consistent with the previously available estimates. The fit in this case converges to a slightly worse reduced χ^2 value of 1.13, with a best-fit metallicity of 0.51 ± 0.04 times solar, higher, as expected, than the best-fit metallicity deduced from a fit converging to a higher interstellar absorption column density. The best-fit temperatures do not appreciably change, being 0.81 and 2.0 keV.

There are unfortunately no photospheric abundance measurements available for VY Ari, and the best-fit coronal metallicity cannot thus be directly compared with the photospheric value. A comparison can however be made with typical photospheric metallicity values for tidally-locked binaries. Randich et al. (1993) and Randich et al. (1994) have derived photospheric lithium and iron abundance values for a large set of active binaries, through analysis of a small segment of their high-resolution optical spectrum, showing that the photospheric iron abundance of RS CVn-type systems, as a class, is significantly lower than the solar one. In particular, the typical range of [Fe/H] values observed in RS CVn binaries lies between $\simeq -0.8$ and $\simeq -0.2$. Thus, the best-fit coronal metallicity for VY Ari, which corresponds to [Fe/H] $\simeq -0.4$, is close to the average of the photospheric abundance values observed for this class of objects.

The best-fit temperatures for the BeppoSAX spectra are rather high when compared with the IPC and PSPC best-fit temperatures. However, the temperatures are comparable with typical coronal temperatures of active binaries derived from the analysis of ASCA SIS spectra. Similar differences between the coronal temperatures derived from the BeppoSAX spectra and from previous analyses have also been seen in the case of Capella (Favata et al. 1997c), and are, at least in part, likely to be due to differences in the plasma emission codes used in the analysis, although the effect of the much more limited energy range observed by either the *Einstein* IPC or the ROSAT PSPC is also likely to play a role, somewhat "forcing" the analysis toward lower effective temperatures for the hotter plasma components. For a discussion of the effects of the detector characteristics on the derived "temperatures" see for example Majer et al. (1986), Wood et al. (1995) and Dempsey et al. (1993). The X-ray luminosity in the 0.16–3.5 keV band resulting from the analysis of the BeppoSAX spectra is 1.1×10^{30} erg s^{-1}, i.e. slightly lower than the IPC- and PSPC-derived luminosities. However, given the typical range of intrinsic source variability observed in this class of objects, the agreement between the measured source luminosities appears to be good.

4. Discussion

The first broad-band coronal spectrum obtained with the LECS and MECS detectors on-board the BeppoSAX satellite is well fit with a two-temperature, optically-thin plasma model, using the MEKAL plasma emission code. With a spectrum of moderate signal-to-noise ratio and spectral resolution, such as the one discussed here, with about 10 kcts in the LECS spectrum, and about 17 kcts in the three MECS spectra, a simple two-temperature model gives a satisfactory phenomenological description of the X-ray spectrum across two decades of energy — between 0.1 and 10 keV. The resulting coronal abundance, at [Fe/H] $\simeq -0.4$ is typical for the photospheric abundance of RS CVn-type binaries.

In this work we assume a two temperature model is a good representation of the coronal structure of VY Ari. As shown by Favata et al. (1997a), simple χ^2 minimization approaches, as currently implemented in X-ray spectral fitting packages, may not always converge, when applied to moderate resolution spectra, toward more complex temperature structures, even when such structures constitute a better (i.e. lower χ^2) representation of the observed spectrum. The differential emission measure (DEM) derived by EUVE has been shown in these cases to be a good starting point for finding a more realistic solution. We will, in a future paper, analyze the VY Ari spectrum in a similar fashion to that performed for Capella by Favata et al. (1997c).

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