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Modelling intermediate polars using the CYCLOPS code: the case of V405 Aurigae

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Abstract. V405 Aurigae is considered the strongest magnetic field Intermediate polar. Previous studies of this system did not succeed when proposing a geometry that explains both the optical and X-ray data. In this study, we present an attempt to reproduce the optical broadband (UBVRI) circular polarization and photometry, as well as the X-ray spectrum and light curve of V405 Aur by using the CYCLOPS code. It was developed to perform multi-wavelength fitting of the accretion column flux and takes into account cyclotron and free-free emission from a 3D post-shock region, which is non-uniform in terms of density and temperature. Our preliminary results indicate that an one-region model is able to explain the observed data. Our results also confirm the strong magnetic field (B = 36 MG), making V405 Aur a possible progenitor of a polar.

Resumo. V405 Aurigae é considerada a polar intermediária com maior campo magnético. Estudos anteriores deste sistema não tiveram sucesso em propor uma geometria que explicasse tanto os dados no óptico quanto os de raios X. Neste estudo, apresentamos uma tentativa de reproduzir a polarização circular e a fotometria no óptico nas bandas UBVRI, bem como o espectro e a curva de luz de raios X de V405 Aur usando o código CYCLOPS. Este código foi desenvolvido para ajustar multi-comprimentos de onda do fluxo proveniente da coluna de acreção e considera a emissão cíclotron e livre-livre de uma região pós-choque 3D, que é inohomogênea em termos de densidade e temperatura. Nossos resultados preliminares indicam que o modelo de uma região é capaz de explicar os dados observados. Nossos resultados também confirmam o alto campo magnético (B = 36 MG), o que torna V405 Aur uma possível progenitora de uma polar.

Keywords. magnetic fields – polarization – novae, cataclysmic variables – star individual: V405 Aurigae

1. Introduction

Intermediate polars (IPs) are magnetic cataclysmic variables binary systems in which mass transfer occurs from a low-mass star onto a magnetic white dwarf (WD). In IPs, the WD magnetic field partially controls the accretion geometry, however it is not strong enough to synchronize the spin period of the WD with the orbital period. Accretion onto the WD occurs via magnetic columns or curtains and far from the compact object there may exist an accretion disk, depending on the magnetic field intensity and secondary mass loss. IPs are reviewed in Patterson (1994).

Magnetic accretion forms a shock near the WD and the compressed material. The post-shock region (PSR) is characterized by the density increase toward the WD surface and the lowest temperature. PSR physics is very similar in polars and IPs. The cooling process occurs via hard X-ray (kT~10 – 60 keV, bremsstrahlung radiation), X-ray emission lines, and cyclotron radiation (Aizu 1973; Wu 1994; Cropper et al. 1999). The soft blackbody emission (kT~20 – 60 eV) is generally observed in polars and in a small group of IPs. The soft X-rays arises from the reprocessing of the hard X-rays in the WD photosphere (Anzolin et al. 2008; Katajainen et al. 2010; Mukai 2017). About 69% of the soft IPs also have polarized radiation detected in the optical and/or near-IR (Butters et al. 2009).

V405 Aur (RX J0558.0+5353) was discovered by ROSAT All-Sky Survey (0.1 – 2.5 keV) and classified as IP by Haberl et al. (1994). The WD spin period is 545.45 s and the orbital period is about 4.15 h (Allan et al. 1996; Skillman 1996). V405 Aur is a soft IP. The component in soft X-rays has shown double-peaked modulation at the WD spin period, whereas the hard X-ray shows a single-peaked modulation. The double-peaked pulsation has been interpreted as the result of two accreting regions in a system with a large angle between the spin and magnetic axes. The simultaneous UBVRI circular polarimetry data show variation between positive and negative values also indicate two-pole accretion. However, the geometry proposed to explain the optical data $30° < i < 50°$ and $\beta = 90°$ (Piirola et al. 2008) is not the same used to model the X-ray data ($i = 65°$ and $\beta = 60°$) by Evans & Hellier (2004).

One important conclusion drawn by Piirola et al. (2008) is that the prediction of the constant temperature cyclotron model was not confirmed by the broad band circular spectrum. Therefore, the authors suggest that any attempt at modelling the cyclotron spectrum should consider the physical parameters of the source region, i.e., temperature, electron number density and the magnetic field, as inhomogeneous. For this reason, the CYCLOPS code is a good approach to modelling V405 Aur.

In this paper, we report a simultaneous modelling of V405 Aur optical and X-ray data. The CYCLOPS code is applied for the first time to IPs and some implementation have been performed. This paper is organized as follows. Section 2 describes the observational data. Section 3 presents the modelling using the CYCLOPS code. In Section 4, we discuss the preliminary results.

2. Observations, data reduction and ephemeris

V405 Aur was observed by the XMM–Newton satellite (Jansen et al. 2001) for 2 h beginning at about 22:27 UT on 2001

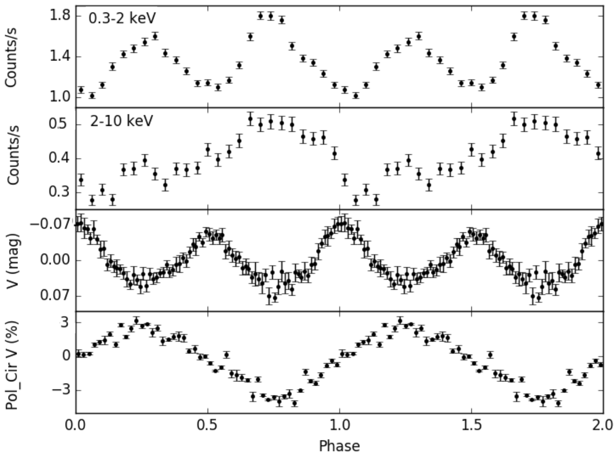

Figure 1. X-ray and optical light curves of V405 Aur folded on the optical ephemeris. From top to bottom, soft and hard X-ray data, photometry and circular polarimetry in V band.

October 4 and ~ 9 h at ~ 22:03 UT on 2001 October 5. We have used the data on October 5 from the EPIC-MOS 2 operating in timing mode (observation ID 0111180401). There is no PN camera data and the source was outside the Optical Monitor window. These data were presented in Evans & Hellier (2004). As we need the instrumental response files, we reduced these data, as described below.

The calibrated event lists were generated by using the SAS software v15.0.0. The background was not extracted, timing mode has limited spatial coverage and V405 Aur is the brighter X-ray source in the field of view. We obtained better results doing the extraction of the MOS background taken in timing mode in same event file used for source, differently of the procedure described by SAS Threads[1].

V405 Aur optical data were kindly provide by Vilppu Piirola (Piirola et al. 2008). The data were obtained using TurPol (Piirola 1988) polarimetric instrument installed at 2.5 m Nordic Optical telescope at Roque de los Muchachos Observatory on La Palma. We have modelled the data from 2003 September 22.

We present a corrected ephemeris to the X-ray data in comparison to Evans & Hellier (2004). The phase zero corresponds to the higher peak of the soft X-rays light curve. BJD_{TDB} is the barycentric dynamic time, which is obtained after conversion of local satellite frame to Barycentric Julian Date.

$$BJD_{TDB}^{max} = 2452187.57416(4) + 0.0063E\ . \tag{1}$$

Our data are shown in Figure 1. To be consistent with optical data, the X-ray light curves were folded on the optical ephemeris calculated by Piirola et al. (2008). We converted their ephemeris from HJD to BJD, BJD_{TDB} 2449681.464617 + 0.0063131476E.

3. CYCLOPS modelling

CYCLOPS – an acronym for CYCLOtron emission of PolarS – is a code to model the continuum optical and X-rays emission from the PSR by cyclotron and bremsstrahlung emission. The code considers the three-dimensional (3D) accretion column and non-homogeneity in terms of temperature and density (Costa et al. 2009; Silva et al. 2013). In addition to these versions, CYCLOPS now allows us to calculate the X-ray light curve.

This paper presents some new implementations in the CYCLOPS code. We implemented interstellar extinction correction in the optical regime using the extinction law from Cardelli et al. (1989), $R = 3.1$ and a gas-to-dust ratio, N(H)/A(V), equals to 2.08 $\times$ 10^{21} H cm^{-2} mag^{-1} from Zhu et al. (2017). The hydrogen column density is a multiplicative parameter in the CYCLOPS code and can be either fixed or fitting. In our modelling, this value is fixed $N_H = 5.805 \times 10^{20}\ cm^{-3}$. It was calculated by Equation 2. The colour excess (E(B-V) = 0.09 ± 0.02) was estimated through the 3D extinction maps[2]. We used the distance obtained by GAIA DR 2 catalogue, $661.82^{+13.21}_{-13.7}$ pc (Bailer-Jones et al. 2018).

$$N_H = 6.45 \times 10^{21} \times E(B-V)\ . \tag{2}$$

The optical fluxes are calculated using a multifrequency approach. We used three (UBV) or five (RI) wavelengths with their respective weights for each band. But, more important, in order to find the best geometry that explains both cyclotron and hard X-ray emissions, we include the X-ray light curves to model simultaneously with optical data and integrated X-ray spectra.

In a preliminary study, we do not restrict the geometry of the system in favor of any values pre-established by the literature. The parameters model were determined using PIKAIA and AMOEBA algorithms (Charbonneau 1995; Press et al. 1992). Figure 2 shows our best-fitting model (i.e. the one with the smallest χ^2) and Table 1 presents its parameters. The model only uses one PSR and reproduces reasonably the V405 Aur data. CYCLOPS does not model emission lines, thus we removed the Kα iron emission line region from the X-ray data: 6.0 – 7.2 keV range. We also removed E < 2.0 keV for showing soft blackbody component.

4. Discussion and conclusions

The simultaneous modelling of V405 Aur using CYCLOPS code with UBVRI optical photometry and polarimetry, hard X-ray spectrum, and X-ray light curve data performed with one PSR is a good model. Although previous studies have been used two accretion regions. We will explore this scenario in the next steps of our modelling despite it will include more parameters in the fitting and demands a longer computational time.

The magnetic field intensity of V405 Aur is estimated as being ~31.5 ± 0.8 MG from simultaneous UBVRI circular polarimetry by Piirola et al. (2008). For these authors, it may indicate that V405 Aur is a likely candidate for a polar progenitor. In our modelling, the best fitting is B = 36 MG. This value has the same order as the value of the literature. However, the synchronism is still far, the ratio of the spin to the orbital period is 0.0365.

The best fitting shows the inclination equals 45.3°. It is within the inclination range estimated from X-ray data (30° – 50°). The colatitude (~59°) is approximately the value given by the data in the optical band, $\beta = 60°$. Our modelling results in a high temperature (T = 358.5 keV), probably because the shock structure used in the present version of CYCLOPS is a poor approximation. A new version of CYCLOPS that solves the shock structure is under development and will probably provide a more realistic shock temperature (Rodrigues et al. 2019, in preparation).

[1] https://www.cosmos.esa.int/web/xmm-newton/sas-thread-mos-spectrum-timing

[2] The 3D extinction maps: http://argonaut.skymaps.info/

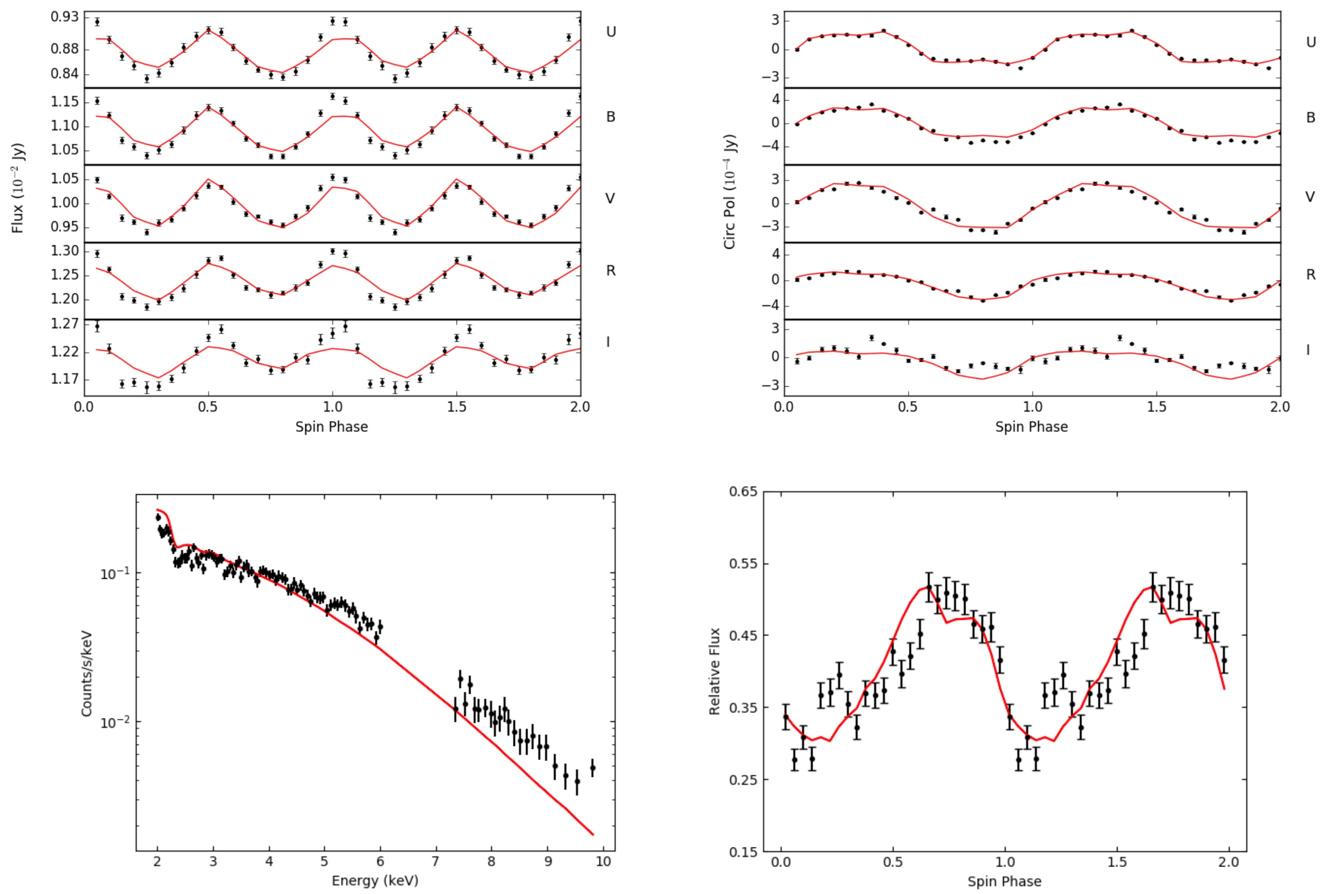

FIGURE 2. A good model of V405 Aur obtained by a simultaneous fitting of UBVRI light and polarization curves (top), X-rays spectrum, and hard X-ray light curve (bottom).

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Table 1. Best-fitting model parameters of V405 Aur.

CYCLOPS input parameters	Description	Fitted values
i	orbital inclination	45.3°
β	colatitude angle	59.1°
Δ_{long}	one-half of the azimuth of the threading region	64.5°
Δ_R	one-half of the radial extension of the threading region	0.055
h	height of the post-shock region	0.53 R_{WD}
f_l	position in the longitudinal direction of the threading point	0.500
B_pole	polar magnetic field intensity	36 MG
B_lat	latitude of the magnetic axis	67°
B_long	longitude of the magnetic axis	37°
T_{max}	maximum electronic temperature	358.5 keV
$log(N_{max})$	log of maximum electronic density	12.26 cm^{-3}
Model result	**Description**	**Value**
B_{reg}	magnetic field in the post-shock region	7 – 27 MG
$\langle T \rangle$	mean eletronic temperature	165 keV
T_{pond}	temperature weighted by the square density	112 keV
T_{range}	range of temperatures of in the post-shock region	33 – 331 keV
δ_{phase}	phase shift applied to the model	0.72
χ^2_{pond}	chi-squared weighted with errors	1042
χ^2_{norm}	chi-squared normalized	0.121
R_s	radius of spot base	2.22×10^7 cm
A_s	spot area	4.96×10^{14} cm^2
H_s	spot height	3.38×10^8 cm