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Pure cyclotron spectra of V405 Aur

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HIGHLIGHTS

- We model the pure cyclotron spectra of an IP, V405 Aur.
- We check the consistency of our model with observations.
- Our model successfully reproduced the observations.

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ABSTRACT

In this study we investigate the pure cyclotron spectra of an Intermediate Polar (IP), V405 Aur, which has the highest magnetic field strength in its class. Recent studies have shown that cyclotron harmonics are seen in the spectra of V405 Aur. We assume that cyclotron harmonics are produced by electrons having a streaming bi-Maxwellian velocity profile found in the lower portions of the accretion column connecting to the magnetic poles of the white dwarf in V405 Aur system. Then we applied the Green function for a dispersive medium such as the one found in V405 Aur. Further we assume that the cyclotron radiation is produced at Ordinary and Extraordinary wave modes. We find the general solution of the Green function for the Extraordinary wave mode and a dispersive medium and we derived the pure cyclotron spectra from the Green function. This function enabled us to calculate energy radiated per unit wavelength per unit solid angle as a function of wavelength which revealed the sixth, seventh and the eighth harmonics which correspond to the observed values. Our model produces the observed cyclotron spectrum of V405 Aur.

1. Introduction

V405 Aur was discovered by Haberl et al. (1994) during the ROSAT all sky survey. V405 Aur is one of the rare IPs showing cyclotron humps in their spectra (Piirola et al., 2008). The magnetic field intensity of V405 Aur as an IP has an extreme value. Other cyclotron radiation properties of V405 Aur can be found in Piirola et al. (2008) and references therein. In this study we try to model the pure cyclotron spectrum of this IP.

IPs form a subclass of the magnetic cataclysmic variables (mCVs). Another subclass of the mCVs , i.e. AM Herculis stars, also known as polars, and IPs are interacting binaries. In these two classes, the primary star is a white dwarf (WD) and the secondary is a late type main sequence star. Due to the strong magnetic field, 10–100 MG (see e.g. Butters et al., 2009) the accreting matter flowing from the secondary towards the WD in polars can not settle in a disc but rather captured by the magnetic field and directed to the magnetic poles via an accretion column. In IPs, since the magnetic field is weaker (1–20 MG) than those of mCVs', the mass donated by the secondary forms a disc around the WD primary until it reaches a critical distance from the WD where the magnetic field guides the disc fluid through an accretion column towards the magnetic poles.

It is known that the maxima of the light curve of V405 Aur in the optical band occur at 0.0 and 0.5 phases when the line of sight is almost perpendicular to the magnetic axis of the WD (Piirola et al., 2008). Other identifying characteristics of IPs are given by many recent papers found in the literature of CVs. An interested reader may be referred to, for example, Ramsay et al. (2008); Cropper (1990); Warner (1995).

2. Dynamics of accreting plasma

Throughout this investigation we use *cgs* units. The disc plasma guided by the magnetic field streams down towards the magnetic

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poles on the WD surface. Its supersonic speed is now controlled by the magnetic mirror force and is decelerated to subsonic speeds. The velocity distribution function of the accreting matter is highly likely in the streaming bi-Maxwellian form. As early as 1990, Schwope et al. (1990) drew attention to the need in considering the non-Maxwellian velocity distribution function. Magnetic field rather than the gravity is a dominant factor in the lower parts of the accretion column. If one is to deal with cyclotron cooling, helical trajectories of charged particles are to be considered. In these helical trajectories their instantaneous velocities have two components, one along and the other perpendicular to the magnetic field lines. The magnitude of their streaming velocity depends on their initial pitch angle where they were captured by the magnetic field. The smaller the initial pitch angle the deeper they can penetrate towards the higher magnitude field regions to seek their respective mirror points. Particles with a great average streaming velocity will emit cyclotron radiation, the angular distribution of which is confined around the instantaneous velocity vector as a dipole and therefore points towards the surface of the WD and in the opposite direction along the "open" field lines.

On the other hand, the particles with greater initial pitch angles will also emit cyclotron radiation but the direction of the emission becomes more perpendicular to the local magnetic field while they approach towards their respective mirror points. Cyclotron radiation emitted perpendicularly to the local magnetic field will be propagated in an Ordinary and Extraordinary mode. The Extraordinary mode is circularly polarized. Katajainen et al. (2010) report that, the IP we are interested in, V405 Aur, together with seven other IPs emit circularly polarized radiation. The polarized radiation in these systems is emitted in extraordinary modes. The Ordinary mode is linearly polarized. Piirola et al. (2008) attributed the very low percentage of the linearized emission to the interstellar medium, and applying the *Serkowski law* to the observed values of linearly polarized emission showed the consistency of their claim with the theoretical prediction. One may also speculate that the observed linearly polarized radiation may be emitted by the ordinary mode in the source region.

For V405 Aur, Piirola et al. (2008) showed that the polarization peak happens to be in the blue part of the optical spectrum. The magnetic field intensity of the V405 Aur is estimated to be $\sim 31.5 \pm 0.8$ MG from low resolution circular spectropolarimetric study (Piirola et al., 2008). And in the spectrum of V405 Aur transient dips which were identified as the sixth, seventh and the eighth harmonics were observed. The authors give the polarization percentages as ±3% in *B* and *V* bands and ±2% in *R* band. The low percentage of the polarized emission may be due to the diluting effects of the background thermal and unpolarized emission. These observations revealed that the magnetic field intensity of V405 Aur is the highest in IPs and equals those of polars (with 25–50 MG). The almost symmetric light variation of positively and negatively polarized emission indicates that both magnetic poles of the WD in the system accrete matter at the same rate.

Piirola et al. (2008) also stressed the very well known fact that the cyclotron radiation emitted by plasma particles accreting towards the magnetic poles of the WD is confined in a solid angle more or less perpendicular to the local magnetic field due to the high pitch angle of the helical trajectories of the particles at the proximity of their respective mirror points.

In their multi colour (*UBVRI*) polarimetric observations of V405 Aur, Piirola et al. (2008) have managed to put constraints on the magnetic field intensity and the geometry of the system. The authors claim that the results of these observations are supported by low resolution circular spectropolarimetric observations. Simultaneous *UBVRI* light curves of V405 Aur show minima at 0.25 and 0.75 phases when the line of sight (*los*) is along the magnetic field lines in accretion column. On the other hand, at phases 0.0 and 0.5 when the *los* is perpendicular to the magnetic field lines light curves are at maxima (see Fig. 2 in Piirola et al., 2008). Figs. 7 and 8 in Piirola et al. (2008) show their model derived from the observations.

Anzolin et al. (2009) found in their observations heated spots with different sizes and temperatures and argued that they could be explained by bremsstrahlung and cyclotron radiation if these two radiation mechanisms play a role in irradiating the WD surface in V405 Aur. Anzolin et al. (2009) also report that RX J2133 and V405 Aur show polarized optical emission. In particular, Shakhovskoj and Kolesnikov (1997) argued that optical/near-IR circular polarization in V405 Aur spectrum suggests that cyclotron radiation plays an important role in irradiating the WD surface.

The most important conclusion is that the source of the beamed cyclotron radiation is at the higher part of the post-shock region (Anzolin et al., 2009). The magnetic field in the accretion column is inhomogeneous, i.e., magnetic bottle like, besides, streaming bi-Maxwellian velocity profile although represented by an average streaming velocity, intrinsically has various particle velocities and temperatures. When combined, all these effects cause the broadening of the cyclotron harmonics (Butters et al., 2009).

One of the important conclusions 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 they 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 non-homogeneous.

3. Application of the Green function in an accretion column

In this subsection, we will follow the same procedure as is found in Kalomeni et al. (2005) to model the pure cyclotron spectra of V405 Aur. We applied the Green function for a dispersive medium such as the one found in V405 Aur. Let us consider a charged particle at r' which radiates at time t' after having been accelerated by, say, Lorentz force of which the radiation is received at the observer at r and at time t. The Green function represents the wave equation for all the frequencies (ω) conceived. This idea is extended from a point source to a dispersive medium (Jackson, 1975). The *retarded Green function* for the accretion column with n_e radiating electrons, we are considering, is given by:

$$G(r,t;r',t') = \frac{n_e}{4\pi}\int d^3k \int d\omega \frac{exp[i\mathbf{k}\cdot(\mathbf{r}-\mathbf{r}') - i\omega(t-t')]}{k^2-(\omega^2/c^2)} \tag{1}$$

At the lower portion of the accretion column, we assume that the wave frequency, cyclotron frequency and ck, where c is the speed of light in vacuum and the k is the wavenumber, have the same order of magnitude and the electron plasma frequency is very much smaller than the formers. The denominator in the ω integral is to be considered in specific wave mode dispersion relations. In our case, since the cyclotron radiation propagates almost perpendicularly to the magnetic field in the accretion column, the relevant wave modes are the Extraordinary and the Ordinary ones. For single particles the dispersion relations of the Extraordinary mode is (Wu, 1985) ,

$$1 - \frac{c^2k_\perp^2}{\Omega^2} + \frac{\omega_{pe}^2}{\Omega^2}\int d^3v\left(\Omega_{ce}\frac{\partial F_e}{\partial v_\perp} + k_\parallel v_\perp \frac{\partial F_e}{\partial v_\parallel}\right) \times \frac{v_\perp (J_1')^2(b)}{\left(\omega - \frac{\Omega_{ce}}{\gamma} - k_\parallel v_\parallel\right)} = 0 \tag{2}$$

and for the ordinary mode (*ibid*),