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Hγ LINE SPECTRUM OF INTERMEDIATE POLARS

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ABSTRACT

Kim & Beuermann (1995, 1996) have developed a model for the propagation of X-rays from the accreting white dwarf through the infalling material and the re-emission of the energy deposited by photo-absorption in the optical (and UV) spectral range. By using this model, we calculate the profiles of the Hγ emission-line spectrum of intermediate polars. Photoabsorption of X-rays by the infalling material is the dominant process in forming the observed energy-dependent rotational modulation of the X-ray flux. X-ray and optical modulations are sensitive to model parameters in different ways. In principle, these dependencies allow us to obtain improved insight into the accretion geometry of the intermediate polars. We present results of our calculations and compare them with the Hβ line spectrum (Kim & Beuermann 1996).

1. INTRODUCTION

Intermediate polars are magnetic cataclysmic variables containing a mass-accreting magnetic white dwarf and a late type main sequence star. They seem to have a weaker magnetic fields than polars, the other subclass of magnetic cataclysmic variables. An accretion disc may be present in intermediate polars, but is not in polars. At some radius where the ram pressure and magnetic pressure are equal, this accretion disc is disturbed by the magnetic field and the accretion flow follows the polar field lines. Near the stellar surface the material passes a standing shock and hard X-rays is produced from the $\sim 10^8 K$ post shock plasma. Half of the emitted flux will be directed towards the stellar surface and either be reflected by Compton scattering or re-radiated as quasi-blackbody emission in the form of soft X-rays or UV radiation. Hard X-rays are partially absorbed in the magnetospheric stream on its way to the observer (Hameury *et al.* 1986). The varying amount of photo-absorption as a function of rotational phase causes the modulation of the X-rays and the modulation of the re-emitted flux (Rosen *et al.* 1988, Norton & Watson 1989, Kim & Beuermann 1995, 1996). For the characteristics and current problems of intermediate polars, see the review by Patterson (1994).

Kim & Beuermann (1995, Paper I) have developed a phenomenological model for the accretion onto the magnetic white dwarf and the propagation of the emitted X-rays through the infalling material. They showed that photo-absorption could produce the observed energy-dependent rotational intensity modulation. According to their parameter study, the modulation is sensitive to the accretion rate, the degree of clumpiness in the accretion stream, the tilt of the magnetic axis, and the inclination of the system. However, the dependency on the parameters of the white dwarf and on the physical conditions imposed on the accreting matter at the point of injection from the disk into the magnetosphere is small. In a follow-up paper (Kim & Beuermann 1996, Paper II), we extended the model to calculate the optical spectrum which originates from the reprocessing of X-rays in the accretion funnel. The results of this study show that the optical continuum forms in the inner optically thick part of the stream, whereas the outer optically thin part dominates the line emission. The calculated Hβ line profiles display complicated structure which depends on model parameters in a different way than the X-ray flux and optical continuum. Such dependency suggests that more detailed calculations will provide useful diagnostic tools in the study of intermediate polars.

The main purpose of this paper is to investigate the model dependency of the theoretical Hγ line profiles by using the phenomenological model of Kim & Beuermann (1995, 1996) in an attempt to provide the tools necessary for the direct comparison with observation. The results of this calculation are compared with the Hβ line profile calculations by Kim & Beuermann (1996). We will also discuss the applicability of the model to analyse observational data on intermediate polars.

2. MODEL CALCULATIONS

A partial-covering model of the accretion stream is adopted in order to describe the absorption of X-rays in the infalling matter. In this model, part of the X-ray flux emerges without absorption. For practical purposes, we divide the annular emission region surrounding the upper and lower magnetic poles into 36 point sources respectively. For a given phase, the X-ray spectrum outside the system is obtained by adding up the contributions from the 2×36 point sources appropriately propagated through the absorbing matter (see paper I).

The magnetospheric stream is divided into 36 sections in longitude of which each is again divided into 20 poloidal segments. For each segment, we calculated the absorbed energy and the re-processed optical spectrum assuming local thermal equilibrium (LTE). The observed optical flux is then calculated at a given phase by adding up the optical spectrum of all visible segments taking the Doppler shifts into account in case of the Balmer line profiles. For more details see Kim & Beuermann (1995, 1996).

Similar to the Hβ case (Paper II), we calculate some global quantities of the Hγ line, as the equivalent width $W_{H\beta}$ and the violet to red line flux ratio (V/R ratio), along with the line profile. These global quantities will provide information on the funnel geometry. We define a specific set of parameters as our reference model and let individual parameters vary around the reference parameters (see Table 1 in Paper I). The reference model is close to the set of parameters appropriate for the system EX Hya as determined by Hellier *et al.* (1987).

3. Hγ LINE SPECTRUM AND DISCUSSION

Figure 1 presents examples of model dependent Hγ line profiles calculated for rotational phase ϕ=0.5. Individual profiles are shifted upwards by a constant amount. The line emission originates

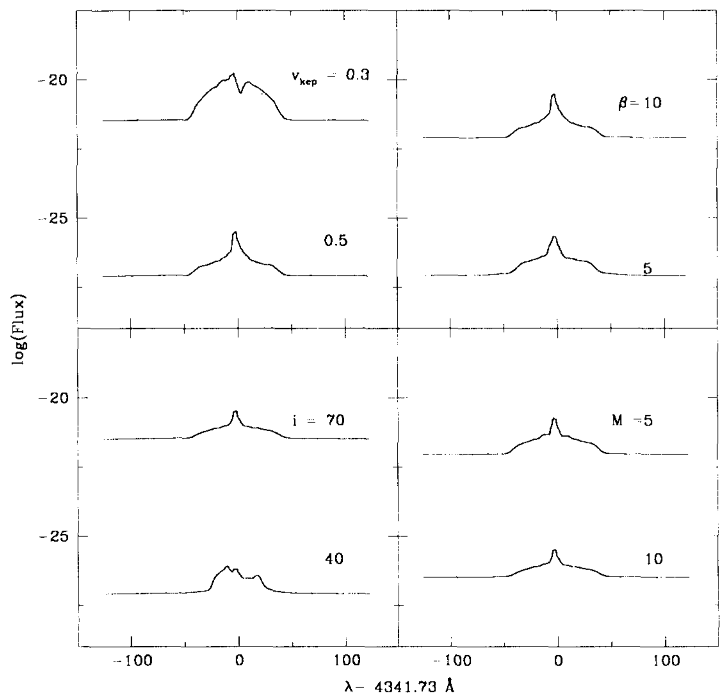

Figure 1. Model dependence of theoretical Hγ line profiles calculated at the rotational phase ϕ=0.5 with reference parameters for two different model parameters.

from the heated matter in the accretion flow and our study shows that the peak flux of the Hγ profile is produced in the outer magnetosphere where matter moves along the magnetic field lines away from the disk, similar to what we discussed in the case of Hβ (Paper II).

The line shape is found to depend more sensitively on model parameters than the X-ray flux presented in Paper I. Figure 1 also shows that the inclination of the system and the injection velocity from the disk into the magnetospheric stream affect the shape of Hγ line emission more than the accretion rate or the offset angle of the magnetic axis from the rotational axis. Comparison of the present results with those obtained for Hβ (Paper II) shows that the Hγ line profiles vary similarily to those of Hβ (see, however, below). For example, the Hγ line profile becomes broader as the injection velocity decreases, which can be understood by the following scenario. Given a mass flow rate, an increased injection velocity causes the density in the outer stream to decrease, the line emissivity at small velocities to decrease, and the relative contributions by the inner segments of the accretion flow to increase correspondingly: the profile broadens.

Another characteristic feature of Hγ as well as Hβ is the double-peak structure (Figure 1). This structure arises from the partial streams to both poles being antiparallel and suggests that the

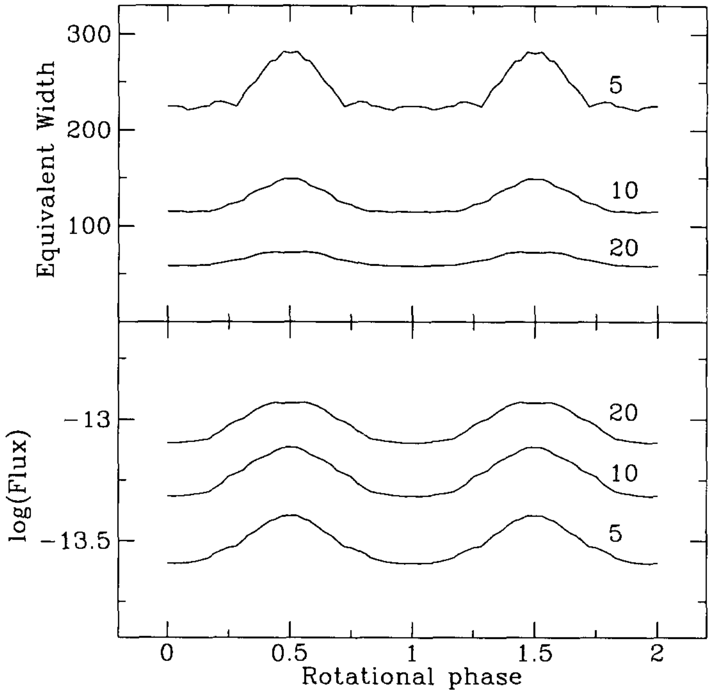

Figure 2. Equivalent widths and integrated line flux of the calculated Hγ line profiles for accretion rates of 20, 10 and 5 $\times$ $10^{16} gs^{-1}$.

occurrence of double peaks in the spectra of intermediate polars may not necessarily represent a unique evidence for the presence of an accretion disk. In view of the approximate treatment of the radiative transfer, a more detailed study of the funnel flow is required to exclude the possibility that such peaks may be mistaken for disk lines. We note that the evidence for large geometrically thin accretion disks is controversial (Warner 1985, Hameury *et al.* 1986, Patterson 1994).

We further analyzed the Hγ line profiles by calculating the equivalent widths and the V/R ratio. Figure 2 presents the equivalent width and the integrated line flux of Hγ as a function of rotational phase for accretion rates of 20, 10 and 5 $\times$ $10^{16} gs^{-1}$. We find that the equivalent width increases with decreasing accretion rate. Smaller accretion rate corresponds to lower density in the stream of which a larger fraction will then be optically thin. Combined with our results of Paper I and II, the calculations correctly describe several basic properties of intermediate polars, demonstrating that the adopted model is basically correct.

In paper II, we reported that the value of V/R near $\phi = 0$ strongly depends on the inclination, i, changing from a minimum with $V/R < 1$ at high inclination to a maximum with $V/R > 1$ at low inclination. This dependency on i makes the V/R light curves a potentially important diagnostic

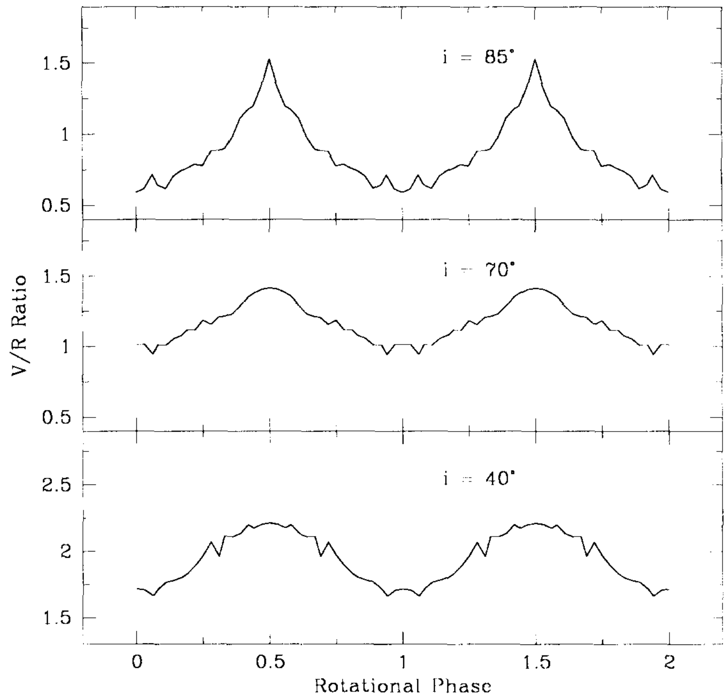

Figure 3. V/R ratio of Hβ line profiles for inclinations of 40°, 70° and 85°.

tool. Figure 3 shows that the V/R of Hγ assumes a maximum at $\phi = 0.5$ and a minimum at $\phi = 0$ for different inclinations. The V/R ratio of Hγ behaves differently from Hβ, suggesting a strong variation along the Balmer series and requiring a more detailed investigation.

4. SUMMARY

We have calculated the Hγ emission line profiles which originate from the accretion funnel of the magnetic white dwarf in intermediate polars. Our present calculation has pilot character and indicates that constructing the internally consistent model for the X-ray and optical modulation is feasible. Our basic model is similar to that of Hellier (1997) and Hellier *et al.* (1997). The results we have obtained so far can be summarized as follows:

1. Rotational modulation of the X-ray flux and the optical continuum can be explained by the combined action of photo-absorption of X-rays in the accretion flow and re-emission in the optical range.

2. The continuum originates from the inner dense and strongly illuminated funnel, the emission line spectrum (Balmer lines) from the less dense and optically thin outer accretion flow.
3. The rotational modulation of the Hγ line profiles is particularly sensitive to the injection velocity of matter from the disk into the magnetosphere.
4. The prime parameter affecting the V/R light curve of $H\gamma$ is the inclination of the system. The V/R light curves differ in structure from the $H\beta$ light curve, requiring a more detailed study of the behaviour along the Balmer series. In principle, these properties can be used as diagnostic tools to derive the physical parameters of the accretion flow.

The calculation of the line profiles of the other Balmer lines and a comparative study of theoretical and observational light curve are in progress.

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