REPROCESSING OF *Lc* IN IRRADIATED ATMOSPHERES OF UNEVOLVED COMPANIONS IN PRECATACLYSMIC BINARIES (PCB) AS A SENSITIVE TOOL OF MEASURING THE TEMPERATURES OF HOT SUBDWARF PRIMARIES

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ABSTRACT. We report results of modeling physical processes in the outermost layers of strongly irradiated atmospheres of low mass companions in PCBs where *Lc* radiation coming from the hot subdwarf (sdw) primary is reprocessed. We solve explicitly a set of equations of hydrostatic, ionization and thermal equilibrium and calculate the intensity of reprocessed emergent radiation in recombinations for optically thin plasma. For purely hydrogenic atmosphere and typical for PCBs values of incident fluxes, densities, gas pressures of irradiated upper atmospheric layers we find that *Lc* will be absorbed and re-emitted in recombinations within the column of effective thickness $(10^6 - 10^8) cm$ of HII depending on the electron density and the effective temperature of sdw. The most interesting and non-trivial result of our model computations lies in the overheating of the uppermost layers of irradiated atmosphere: the equilibrium temperature of gas turns out to be considerably higher than the value of radiative temperature in the black body approximation following from the total irradiating flux of the diluted incoming radiation of sdw. This result enables one to explain the abnormally high values of albedos following from the conventional analysis of the light curves of PCBs (amplitudes of the light curves correspond to albedo values typically amounting to $3 - 5$ for well-studied systems like $V477Lyr$). The effect of overheating is determined solely by the effective temperature of irradiating source. Thus, we indicate how the effect of reprocessing of *Lc* radiation can be used as a sensitive tool for a more rigorous determination of the effective temperature of the sdw primaries in PCBs.

Key words: Stars: binary: precataclysmic, reflection effect.

1. Introduction

PCBs is a group of close binary systems composed of a sdw or a white dwarf precursor (primary star) and an unevolved secondary star, usually a red dwarf. Periods of these systems are very small, varying from several days to several hours, and separations between the components are also small, so systems are close. Nonetheless, they are still not close enough for the secondary's Roche lobe to be filled, so cataclysmic activity hasn't yet started. PCBs are frequently found to be the cores of planetary nebulae.

It is generally accepted now that such systems originate from wider binaries as a result of the common envelope stage that once took place in course of their evolution. The common envelope originates, when the more massive primary fills its Roche lobe and begins to loose matter forming a shell embracing the system and effectively brakes it down, forcing the secondary to spiral down towards the common gravity center. Thereafter the matter is expelled from the system and is observed as a planetary nebula.

One of the most spectacular particularities of PCBs is an extremely high reflection effect. Being only a second order effect in common semi-detached systems, it is often the main cause of optical variability in such close systems as PCBs. Due to the fact that the distance between the components is very small (about some units of solar radius) and that the effective temperature of the primary is extremely high (tens of thousands Kelvins), the hemisphere of the secondary facing the primary star is highly overheated. The physics standing behind the emergent radiation transformations in the overheated phototosphere of the secondary, is very complicated; that is why we cannot treat the flux escaping from the secondary's illuminated hemisphere as simply as it is usually done in conventional models of reflection effect in ordinary semi-detached systems (see, for instance, Paczynski and Dearborn 1980).

An adequate model of the processes involved in the transformation of the incoming hot radiation in the photosphere of the secondary star would let one to obtain independent estimations of the system's parameters, including so important one as temperature of the white dwarf. Such model would also help us to predict the future evolution of the system, to answer the question if it has enough time to start cataclysmic activity. Some specific questions, like an unusually high reflection albedo found from observations, could also be answered (see for instance, Pustylnik and Pustynski 1999).

2. Model for upper layers of irradiated atmosphere.

We developed a theoretical model of the upper photosphere of the secondary.

As already mentioned above, effective temperatures of the primary correspond to absolutely black body temperatures of some tens thousands Kelvins. It means that a significant portion of the incoming flux energy is concentrated in the far ultraviolet portion of the spectrum, namely in the band with wavelengths shorter than Lyman limit. This hard flux falls onto rarefied layers of the secondary's photosphere, and processes in these layers are somewhat similar to the processes taking place in planetary nebulae. This fact justifies application of similar methods in our model. It is intuitively clear that there shouldn't exist local thermal equilibrium in such overheated medium. To escape sophisticated non-LTE calculations that would make our reflection effect model extremely complicated, we suppose upper non-LTE layers to be purely hydrogenic and describe them generally in the on-the-spot approximation by the system of three equations: the equation of ionization balance

$$N_0(r)\,W_\delta \int_{\nu_{Ly}}^{\infty} \frac{B_\nu(T_1)\,k_\nu[T(r)]\,exp(-\tau_\nu(r))}{h\,\nu}\,d\,\nu =$$

$$= N_e(r)\,N^+(r)\,\alpha[T(r)]\ .$$

the equation of thermal equilibrium

$$N_0(r)\,W_\delta \int_{\nu_{Ly}}^{\infty} \frac{B_\nu(T_1)\,k_\nu[T(r)]\,exp(-\tau_\nu(r))}{h\,\nu\,(h\nu - h\nu_{Ly})^{-1}}\,d\,\nu =$$

$$= 4\pi \int_0^{\nu_{Ly}} \epsilon[T(r),\,N_e(r)]\,[1+\tau_\nu(r)]\,d\,\nu\ ,$$

and the equation of hydrostatic equilibrium

$$N(r) = \frac{P_{r=0}}{[1+X(r)]\,k\,T(r)}\,exp(\frac{m_p\,G_\delta\,r}{[1+X(r)]\,k\,T(r)})$$

Here

$$X = 1 - \frac{N_0}{N_0 + N_e + N^+}$$

stands for ionization degree (it is unit when all hydrogen is ionized and is zero when all hydrogen is neutral), α is the recombination coefficient to all levels except the first one, ϵ is the total emission coefficient for recombinations, N_0 , Ne, N^+ are respectively the number density of neutral H atoms, of free electrons and protons, B_ν is the Planckian, W_δ is the local value of dilution factor, δ being the angular distance from substellar point of irradiated component, $\tau_\nu(r)$ - the monochromatic radial optical depth counted from the surface of the star, P is the gas pressure (the meaning of other notations is self-explanatory). We neglect the number of ionizations from upper levels in equation of ionization equilibrium. We add the optical depth-dependent coefficient into the right-hand-side integrand of the thermal equilibrium equation to take into account approximately contribution from diffuse radiation. In the formula for hydrostatic equilibrium we take into account the dependence of effective gravity acceleration G on coordinates of the selected point upon the secondary's surface. The applicability of such simplified description was checked by our numeric estimations which showed, that the upper layer of the irradiated atmosphere is opaque for Lyman continuum photons, at the same time photons with lower energy penetrate freely through the same layer practically without being absorbed; so, the non-LTE layer in the first approximation may be considered transparent for radiation in optical wave-band.

When the above-mentioned system of equations is solved, we obtain models of the upper photospheric layer of the heated secondary's hemisphere. As it could be expected, they demonstrate a certain qualitative analogy with models of planetary nebulae.

It is seen that the radiation penetrates into the photosphere until a certain depth, while ionization degree remains close to unity. Thereafter almost whole flux is absorbed in relatively very thin layer of practically neutral hydrogen.

From our models one may conclude that the greatest portion of the Lyman continuum flux is absorbed in the rarefied upper layer, and the energy of Lyman continuum photons is reprocessed into energy of less-energetic quanta, as a result of hydrogen ionization from the ground level and subsequent recombinations onto upper levels, and in addition is expended on heating electron gas. Thus, the reprocessed radiation has a typical recombination spectrum, and its intensity may be obtained from the equation

$$\epsilon[T(r),\, N_e(r)] = \frac{N_e^2}{T(r)^2}\, \Phi_\nu[T(r),\, N_e(r)]\; exp(-\frac{h\nu}{kT(r)}),$$

where

$$\Phi_\nu = 5.4(F_\nu[T(r)] \,+\, G_\nu[T(r),\, N_e(r)])\,.$$

Here $F_\nu[T(r)]$ is the Gaunt factor for free-free transitions and $G_\nu[T(r),\, N_e(r)]$ is the Gaunt factor for bound-free transitions. The normalization coefficient, introduced into this equation to keep emitted energy rate equal to absorbed energy rate, is omitted in this formula. This coefficient differs from unity in our model due to the fact, that the model doesn't include self-absorption that may be important at large wavelengths and its value is found by equalizing the total energy emitted in recombinations to the local value of the incident flux from sdw.

Next we should analyze physical processes involved in transformation of radiation with longer wavelengths. This is the radiation coming directly from the primary star and penetrating through the upper layers nearly without attenuation, and also the radiation reprocessed in the upper layer and penetrating deeper into the photosphere.

The numeric estimations show that the deeper layers may be treated as medium with LTE, and thus we may use diffusion (Eddington) approximation to model them. Following Basko and Sunyaev 1973, we write the Eddington equation in the following form:

$$F_0 \,+\, F(y) = -\frac{16\sigma\, x_H\, \rho(r)\, T(r)^3}{3\, m_p\, k[T(r),\, P(r)]}\, \frac{dT}{dy}\,,$$

where variable y is defined as follows:

$$y(r) = -\frac{x_H}{m_p} \int_0^r \rho(r)\, dr$$

and

$$F(y) = exp(-\frac{2}{3\mu}) \int_{\lambda_{Ly}}^{\infty} F_{inc}\, exp[-yNk(\lambda,\, T,\, P)]\, d\lambda\,.$$

This equation is solved numerically together with hydrostatic equilibrium equation

$$\frac{d}{dr}\, P(r) = G_\delta\, \rho(r)\,,$$

and the results of the solution may be expressed as temperature, pressure and flux functions of the mean optical depth τ that is introduced with the formula

$$\tau(r) = \int_r^\infty k(r)\, dr\,.$$

Having obtained this solution, we may deduce the intensity of emergent radiation from the deeper photosphere:

$$I_\nu(\mu) = \int_0^\infty \frac{1}{\mu}\, \frac{k_{2/3}(\nu)}{\overline{k_{2/3}}}\, B_\nu(T)\, exp(-\frac{k_{2/3}(\nu)}{\overline{k_{2/3}}}\, \frac{\tau_\nu}{\mu})\, d\tau\,.$$

This intensity is function of the angle $\arccos\mu$ with the local normal.

In this way we obtain intensities of emergent radiation escaping from the upper non-LTE and deeper LTE layers of the secondary's photosphere. Taking these two intensity components together and integrating them over the whole visible sector of the secondary at a particular orbital phase, we get the total flux intercepted from the secondary by an observer:

$$L_\nu(i,\theta) = 2R_2 \int_{\delta_{min}}^{\delta_{max}} \int_{\chi=0}^{\chi_{max}} I_\nu(\Psi)\sin(\delta)\cos(\Psi) d\chi d\delta.$$

For different phase angles the observable illuminated sector has different shapes, and thus we may construct a smooth light curves by computing the reemitted radiation input into the total system's luminosity at various phases. We normalize the light curves so, that the total relative luminosity in minimum light were unity:

$$l_{norm}(\nu\,\theta) = \frac{L_1(\nu) + L_2(\nu,\,\theta)}{L_1(\nu) + L_2^{min}(\nu)}\,.$$

3. Results and Conclusions

1. The effective thickness of the column where the total Lc flux is absorbed for typical temperatures $Tsdw\,=\,(40000\,-\,70000)K$ and electronic densities $Ne = 10^{13}cm^{-3}$ amounts to $\Delta r = (10^6 - 10^8)cm$. As we can see from the Figure 1, the thickness of the ionized zone is rather strongly dependent both on the values of Tsdw and the distance from substellar point. Since the emission measure is proportional to Ne^2 it is clear that the contribution from the zones close to the substellar point will be dominant (both Ne and Δr are higher).

The first attempts to substitute black body spectral distribution of the hot subdwarf by the distributions following from the model atmospheres discussed in (Kubat at al., 1999) demonstrate sensitivity of both temperature and ionization degree runs to Lyman continuum of the irradiating source.

2. One of the observational phenomena that receives a natural explanation in our model is a well-known excess of the secondary's albedo coefficient in optical and infrared bands in comparison with estimates made from the models based on simple black body approximation . In our model this discrepancy is explained by

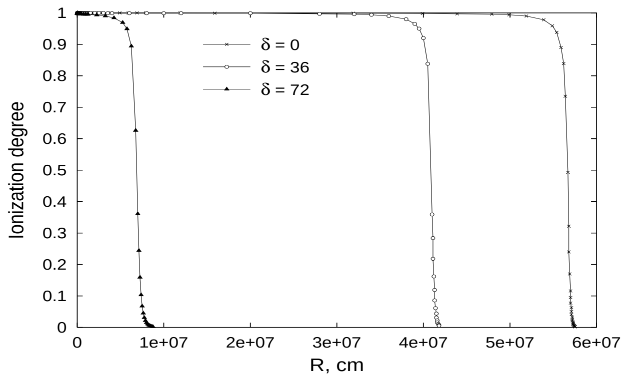

Figure 1: Ionization degree x as function of depth R in irradiated photosphere for different values of angular distance from the substellar point. PCB parameters are: $a = 2R_{\odot}$, $R_1 = 0.01R_{\odot}$, $R_2 = 0.2R_{\odot}$, $M_1 = 0.51M_{\odot}$, $M_2 = 0.15M_{\odot}$, $T_1 = 60000K$, $T_2 = 4000K$, $N_e(0) = 5 \cdot 10^{12} cm^{-3}$.

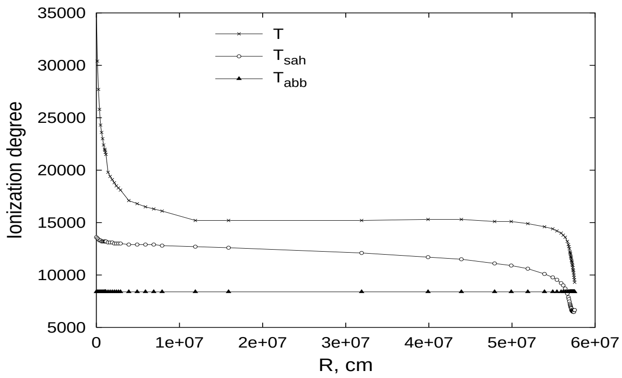

Figure 2: Runs of equilibrium temperature T, ionization temperature T_{sah} and black body temperature T_{abb} in the irradiated photosphere. PCB parameters are the same as in the Figure 1.

the fact, that the energy in the ultraviolet part of the spectrum is reprocessed due to recombinational processes into low-energetic quanta, and thus gives rise to the above-mentioned excess.

3. The high values of albedo from irradiated atmospheres follow from the fact that the upper layers where the Lc continuum is absorbed are strongly overheated. This is illustrated in the Figure 2 where the runs of equilibrium temperature T (following from solution of the set of equations of thermal, hydrostatic and ionization equilibrium), T_{saha} (ionization temperature following from Saha formula for a given local values of electron and neutral hydrogen densities), T_{abb} (black body temperature following from the value of total incident flux from sdw) are compared. As we see T is systematically higher than both T_{saha} and T_{abb}, the difference being progressively larger as one moves towards the uppermost layers of the irradiated atmosphere.

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