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PHYSICAL CONDITIONS ON THE STREAM OF CYG X-1 PRODUCED BY THE X-RAY FLUX

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RESUMEN

Se ha estudiado la interacción de un flujo de rayos X con el gas que fluye de la estrella primaria hacia el objeto secundario, en el sistema Cyg X-1 (HDE 226868). Del análisis de equilibrio térmico y de ionización resultó que, en función de las características de los rayos X incidentes, el gas puede presentar condiciones de inestabilidad que inducen transiciones de fase. Se consideró la posibilidad de explicar las observaciones de la línea en emisión He II λ 4686 mediante este mecanismo.

ABSTRACT

We have studied the interaction of an X-ray flux with the gas in the stream that flows from the primary star to the secondary object in the system Cyg X-1 (HDE 226868). From the analysis of thermal and ionization equilibrium, it turned out that according to the X-ray characteristics, the gas might present instability conditions that induce phase transitions. The possibility of using this mechanism to explain the observations of the He λ 4686 emission line was considered.

Key words: X-RAY SOURCES — BINARIES — BLACK HOLES

I. INTRODUCTION

The source Cyg X-1 has been identified with the binary system HDE 226868, the primary (visible star) of the system being an OB Ib supergiant (Webster and Murdin 1972; Tananbaum *et al.* 1972; Bolton 1972 *a, b, c;* Walborn 1973). There is no evidence of any absorption line spectrum from the secondary (invisible) object, but a peculiar, variable emission has been found, corresponding to the lines Hα and He II λ 4686, which overlap the primary absorption line spectrum (Bolton 1972, *b, c;* Brucato and Kristian 1972; Smith *et al.* 1973; Walborn 1973). Hutchings *et al.* (1973) have found that the He II λ 4686 emission line varies in velocity 120° out of phase with respect to the absorption spectrum, with about 1.8 times its velocity amplitude. The velocity amplitude of the primary star is about 70 km s^{-1}. Bisiacchi *et al.* (1974) have interpreted the radial velocity curve as the resultant of two different velocities: the velocity of a stream of matter which flows from the primary to the secondary, and the velocity due to the rotation of the system. They found the place in the stream that must be emitting the He II λ 4686 line, and they estimated the mass of the secondary object as 10 $M_\odot < M_s < 25\, M_\odot$, assuming for the primary a mass of $M_p = 30\ M_\odot$ (in accordance with its spectral type and luminosity class).

The problem of the physical conditions under which the He II λ 4686 line arises is related to the existence of a mechanism capable of producing enough energy to explain the observed line, and producing it in a region of the stream narrow enough to give a well determined phase shift. In this paper we shall discuss the efficiency of one such possible mechanism: the interaction of the matter in the stream with the X-rays that come from the secondary object. We will evaluate the amount of energy contained in the He II λ 4686 line thus produced.

II. THEORETICAL APPROACH

a) Interaction of X-rays with the gas

In this section, we present a model of a gas heated by a flux of X-rays. There is a considerable uncertainty about the X-ray spectrum of Cyg X-1, particulary for photons with energies below 2 kev. In order to study the physical conditions of the gas. we must know roughly the properties of the X-ray source. Taking into account the observed luminosity and spectrum (Schreier *et al.* 1971; Tananbaum *et al.* 1972), theoretical considerations (Shakura and Sunyaev 1973), and the dimensions of the binary system (Bisiacchi *et al.* 1974), the X-ray flux can be estimated as being of the order of magnitude of 10^{22} photons/cm^2 sec, the energy of the photons being about 1 kev. A more detailed analysis of these data will be given in the conclusions of this paper.

The X-ray flux ionizes the gas. The following processes have been taken into account for the determination of the ionization degree of the gas: primary photoionization, collisional ionization and secondary ionization. The degree of ionization has been calculated for H, He and metals, by means of the following equations:

$$N_eN(H^+)\,\alpha_B\,(H^\circ) = N(H^\circ)\,J_\nu a_\nu(H^\circ) + N_eN(H^\circ)\beta(H^\circ) + F_{sec}(H^\circ) \quad (1)$$

$$N_eN(He^+)\,\alpha_B\,(He^\circ) = N(He^\circ)\,J_\nu\,a_\nu(He^\circ) + N_eN(He^\circ)\,\beta(He) + F_{sec}(He^\circ) \quad (2)$$

$$N_eN(He^{++})\,\alpha_B\,(He^+) = N(He^+)\,J_\nu a_\nu(He^+) + N_eN(He^+)\,\beta(He^+) + F_{sec}(He^+) \quad (3)$$

$$N_eN(M^{(n+1)})\,\alpha_B\,(M^n) = N(M^n)\,J_\nu\,a_\nu(M^n) + F_{sec}(M^n) \quad (4)$$

In these equation J_ν represents the monochromatic X-rays flux in photons cm^{-2} sec^{-1}; Ne and N(X) represent the electron and the X element number densities, respectively. The first member on the left hand side of the Equations (1) to (4) represents the number of recombinations in cm^{-3} sec^{-1}. The recombination coefficients, α_B, used for H, He and He$^+$, are those given by Seaton (1960), Burgess and Seaton (1960), and Hummer and Seaton (1964). The metals taken into account in the calculations are C, N and O, because of their high cosmic abundances. Their relative number densities are: 3×10^{-4}, 10^{-4} and 7×10^{-4} taking the H abundance as equal to 1 (Allen, 1964).

The intensity of the X-ray flux and the energy of the photons are sufficient to ionize the K and L levels of the metals, while maintaining the metals in a very high degree of ionization in the gas. For this reason, we have assumed that only the three highest states of ionization contribute to the equilibrium, in the case of metals. This assumption proved to be correct *a posteriori*. The recombination coefficients for metals have been calculated by means of the approximated formula:

$$\alpha_B(M^{+n}) = (n + 1)^2\,\alpha_B\,(H^\circ) \quad (5)$$

(Allen 1969). The use of this formula is justified by the fact that metals have little influence on the problem. All the coefficientes α_B have been considered as proportional to $T^{-.85}$ (Kaplan and Pikel'ner 1974), where T is the electron temperature. The first term on the right hand side of Equations (1) to (4) represents the primary photoionizations; cross sections, a_ν, for H and He are those given by Rodriguez (1973), and, for metals, those given by Daltabuit (1972). The second term on the right hand side of Equations (1) to (3) represents collisional ionizations; β coefficients being those given by Daltabuit (1972). Collisional ionizations have been omitted for metals, because of the extremely high energies required for this process to occur (energies corresponding to temperatures higher than

10^6 °K). The last term on the right hand side of Equations (1) to (4) represents secondary photoionizations. The ionizations have been analyzed for each element, under the assumption of reabsorption "on the spot". For H^0, the photons considered as ionizing are those produced by ground state transitions of He^0 and those of the Lyman series and Balmer continuum of He^+. For He^0, the photons considered as ionizing are those of the Lyman series of He^+; and for He^+, we consider as ionizing the photons produced by metals. In the case that the number of Lyman photons produced by He^+ exceeds the number of recombinations to H^0 and He^0, these atoms in neutral states are considered to be absent. The assumption was made that the excess photons escape from the gas.

The use of Equations (1) to (4) proved to be correct *a posteriori*. The characteristic time of radiative recombination for $N \geq 10^{12}$ ($t_{rec.} \leq 1$ sec) turns out to be much smaller than the characteristic free-fall time of the stream ($t_{fall} \sim 1$ day); and thus the approximation of thermal equilibrium is good.

The energy balance of the electron gas has been studied by means of the following equation:

$$\sum_{in} (h\nu - X^i_n)\, N(X^i_n)\, J_\nu\, a_\nu(X^i_n) + E_{sec} = kT \sum_{in} N_e N(X^{i+1}_n)\, \alpha_B(X^i_n) + \sum_{in} N_e N(X^i_n)\, \beta'(X^i_n) \qquad (6)$$

where $h\nu$ is the primary photon energy and k the Boltzmann constant. The left hand side of this equation represents the input energy to the electron gas and the right hand side the output energy. The first term on the left hand side represents the energy excess of an electron produced by a primary photoionization; the summation is carried over all the chemical elements and all the ionization states; X^i_n is the ionization potential of the chemical element (n) in the ionizations state (i). The term E_{sec} contains all the contributions due to secondary photoionization, that have been considered before. The energy losses have been considered as due to electron recombination and collisional excitations The coefficients β' are those given by Daltabuit (1972). The densities involved in this problem ($N > 10^{10}$ particles/cm^3) are such that the cooling due to forbidden lines is negligible.

b) *Numerical Results*

The numerical results obtained are shown in Figures 1 and 2. Cooling by collisional excitation of hydrogen dominates in segment ABCDE, whereas, in segment EFG, the cooling is mainly due to collisional excitation of helium. At point C, the collisional ionization of hydrogen becomes more important than primary photoionizations. This reduces the efficiency of cooling by collisional excitation, the result being the raising of segment CDE of the curve. At temperatures around 10^5 K, a similar effect for helium could be expected. This does not happen, however, because, due to the high ionization degree, the input photoionization energy becomes comparable to the energy loss by cascade recombinations. At high temperatures, when H and He are highly ionized, the input energy is determined by the metals. The dotted line in Figure 1 is obtained when metals are included in the calculations.

The effect of taking into account the dielectronic recombination of He^+ (Burges and Summers 1968) has been proved to be negligible. This is due to the fact that $T > 50\,000$°K the emission of Lα photons by collisional excitation of He^+ maintains $N(He^0) \ll N(He^+)$. The ratio $\frac{N(He^{++})}{N(He^+)}$ remains insensible even to considerable variations of α_B (He).

c) *Phase transitions*

If we define $\mathcal{L}$ as the net amount of energy lost by the gas per unit volume and time, then $\mathcal{L} > 0$ above the curve in Figure 1 and $\mathcal{L} < 0$ below it. According to the condition given by Field (1965), the segment CDE of this curve corresponds to states of unestable equilibrium of the gas.

The behaviour of an unstable gas, in condition similar to those just mentioned, has been studied by Zel'dovich and Pikel'ner (1969) and Penston and Brown (1970) for the case of interstellar matter. The results of their work show an analogy with a Van der Waals gas: there exists an isobar corresponding to stable states of the gas with two coexisting phases, B and F, the first one cold and the second

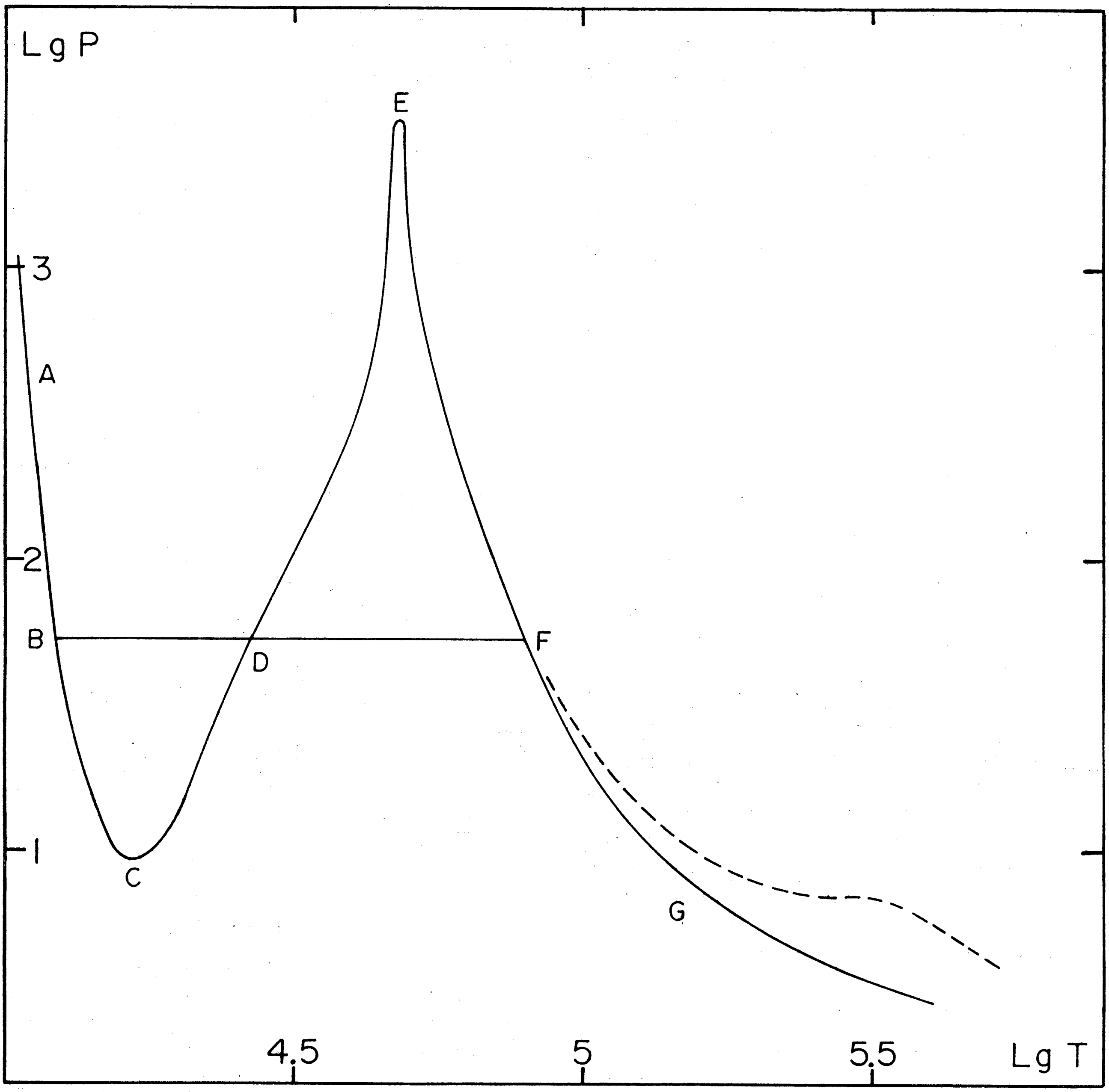

FIG. 1. Pressure *vs.* temperature diagram for equilibrium states of a gas heated by an X-rays monochromatic flux of 10^{19} ev/cm^2 sec and a photon energy of 1 kev. The dashed line corresponds to the correction for the presence of metals.

hot. The criterium for choosing the isobar is that the thermal conduction, in the interphase, compensates the excess of energy absorption or emission, without the matter having to flow from one phase to another. The ionizations state of the gas is such, that we can take thermal conduction as produced by electron conduction (Daltabuit, 1972). We shall consider as equilibrium states those represented by segments AB and FG in Figure 1, whereas segment BF represents two coexisting phases.

Since the matter in the stream goes through different states during its fall, it becomes necessary

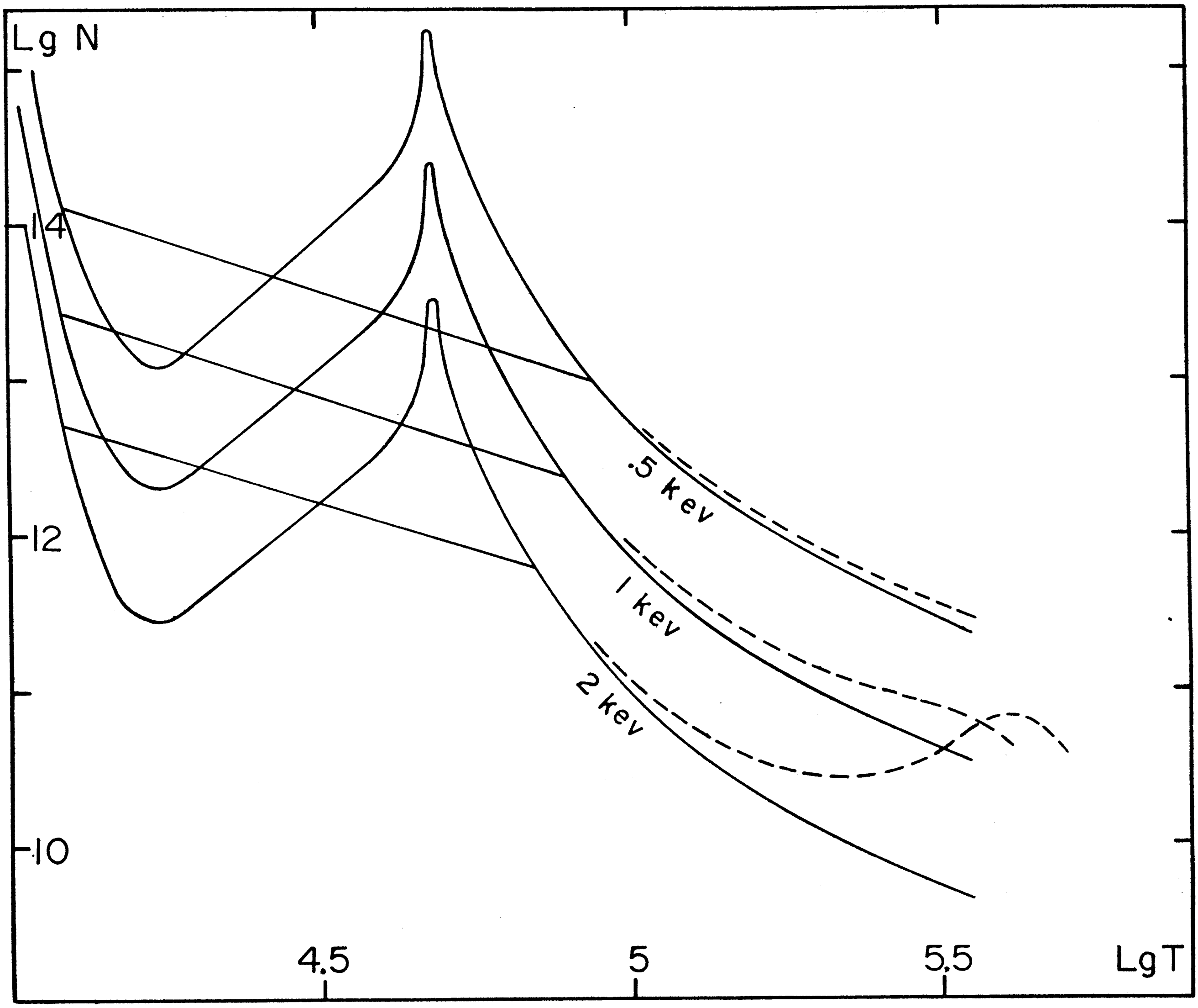

FIG. 2. Density *vs.* temperature diagram for equilibrium states of a gas heated by an X-rays monochromatic flux of 10^{19} ev/cm² sec and photon energies of 0.5, 1 and 2 kev., respectively. The dashed lines correspond to the correction for the presence of metals.

to know whether it evolves through stable states during these phase transitions. By using the method given by Zel'dovich and Pikel'ner (1969) for non-equilibrium states of a gas, we find the following: when an interphase occurs, there is a flux of matter through it of about 10^{-6} gr/cm² sec and the width of the interphase turns out to be a few meters. Under these conditions, it is reasonable to assume that the gas evolves through equilibrium states during the fall.

III. FINAL REMARKS

In this section, the relation between the model presented above and the observational data available for Cyg X-1 (HDE 226868) will be discussed. From photometric studies of absolute stellar energy distributions (Johnson 1972), a typical value was deduced for the energy flux in the continuum spectrum of an OB Ib; at 4700 Å, this flux is equal to 3×10^{34} erg/sec Å. A rough evaluation,

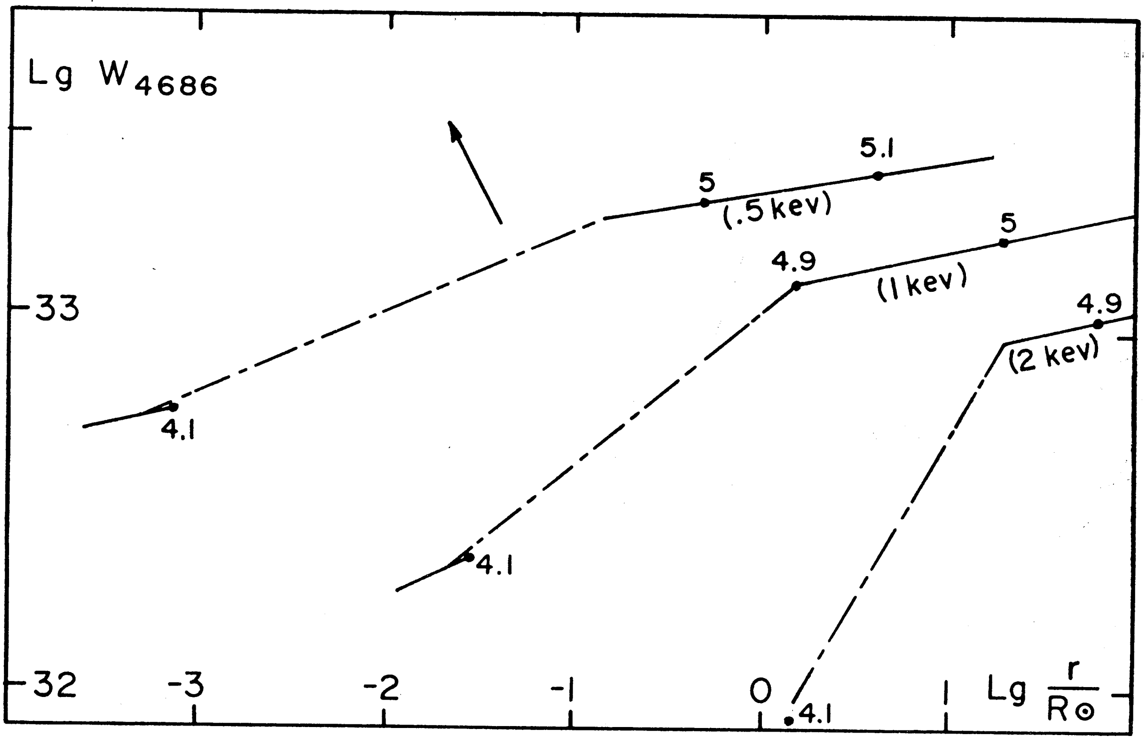

FIG. 3. Emission W in erg/sec, of the He II 74686 line, as a function of depth r of the emitting region, for an X-ray flux of 10^{19} ev/cm² sec and photon energies of 0.5, 1 and 2 kev. The continuous lines represent states of stable equilibrium of the gas. The dashed lines represent phase transitions. The numbers label Lg T. The arrows show how the curves are shifted when the intensity of the X-ray flux becomes double, without changing the energies of the photons.

from the spectra given by Hutchings *et al.* (1973) and Smith *et al.* (1973) showed that the equivalent widths of He II λ 4686 in emission and absorption are equal. Using the criterion and the equivalent widths given by Williams (1936) for the star HD 204172, the amount of energy emitted in the He II λ 4686 line, in the case of HDE 226868, turns out to be approximately 3×10^{33} erg/sec. The width of the stream's section, normal to the velocity of the gas, was taken to be of the order of 2 $R_\odot$; this is the value obtained from an adiabatic expansion of the gas for a free-fall time in accordance with the model of Bisiacchi *et al.* (1974) and a temperature of 30.000°K. Using these dimensions for the stream's section, calculations were made of the amount of energy emitted by the gas at the different equilibrium states. Calculations were also made of the depths reached by the X-rays. The results of these calculations are plotted in Figure 3.

The following conclusions can be drawn from Figure 3: The hot phase is the condition of the gas in which the line He II λ 4686 is more efficiently emitted. This efficiency decreases when the photon energy increases. The depth of the emitting region increases with the photon energy. In order to have a depth of the zone not exceeding 1 $R_\odot$ (which is required by the geometrical model of Bisiacchi *et al.* (1974)), the energy of the photons must be < 1 kev. Unfortunately, precisely in this range, the observational data are very uncertain. A very rough estimation can be obtained by extrapolating the UHURU data to low energies. If the spectrum taken before the transition of April-March 1971 (Tananbaum *et al.* 1972) is considered, the best fit for the X-ray flux below 8 kev is obtained by a power-law spectrum, with an energy index 4.1. Taking the value of the X-ray flux that reaches the earth as equal to 2 photons/cm² sec kev, at 3 kev,

... and considering the distance between the emitting region of the stream and the X-ray source as equal to 13 $R_\odot$, in accordance with the model of Bisiacchi *et al.* (1974), one obtains a flux $J = 1.3 \times 10^{22} E^{-4.1}$ photons/cm^2 sec kev (E is given in kev). Assuming that the cutoff point is at 0.4 kev, and considering the atomic absorption processes related to a spectrum of this kind, this X-ray flux can be simulated by a monochromatic flux of 0.5 kev photons, having an intensity of 4×10^{22} photons/cm^2 sec. From Figure 3, it is seen that for this value of the X-ray flux, the amount of energy emitted by the He II λ 4686 line is in good agreement with observations. In order that the width of the emitting region of the stream should not exceed 1 $R_\odot$, the temperature must not exceed 10^5 K; this temperature corresponds to a density of 0.6×10^{13} cm^{-3}. If the free-fall velocity of the stream is 200 km/sec, which is the value obtained from the model of Bisiacchi *et al.* (1974), the mass loss is $\Delta M/\Delta t = 2 \times 10^{-7}$ $M_\odot$/year. If the cutoff point is at higher energies, the discussed mechanism does not have the efficiency to produce the He II λ 4686 line. This mechanism is not efficient either, when an analogous extrapolation is made for the post-transition spectrum given by Tananbaum *et al.* (1972). It is obvious that the presence of a disc, optically thick for low energy X-rays, would prevent the emission of He II λ 4686 produced by this mechanism. In any case, in order to verify whether the line He II λ 4686 can be generated by the interaction of the X-rays with the gas, according with the model discussed above, it is necesary to have more observational information about the X-ray flux between 0.5 kev and 2 kev.

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