THE ASTROPHYSICAL JOURNAL, 190:L59–L62, 1974 June 1

ON THE INTERPRETATION OF THE He II λ4686 EMISSION LINE IN HDE 226868 (CYGNUS X-1)

G. F. BISIACCHI, D. DULTZIN, C. FIRMANI, AND S. HACYAN
Instituto de Astronomía, Universidad Nacional Autónoma de México
Received 1974 February 25; revised 1974 April 1

ABSTRACT

Two models are studied to explain the origin and behavior of the observed He II emission line λ4686 in the binary system 226868 (Cyg X-1). It is shown that observational data can be quantitatively explained if the line is emitted by a jet of matter flowing from the primary to the secondary. This, in turn, permits us to estimate the ratio μ (mass of the unseen secondary/total mass), which turns out to be $\sim$0.3. The possibility that the line is radiated by a disk rotating with Keplerian velocity around the secondary is very unlikely because of the unrealistic value obtained for the mass of the primary.

Subject headings: binaries — black holes

I. INTRODUCTION

The source Cyg X-1 has been identified with the single-lined binary HDE 226868, with a period of 5.6 days (Webster and Murdin 1972; Tananbaum *et al.* 1972; Bolton 1972*a*, *b*, *c*). HDE 226868 is a ninth-magnitude OB supergiant (Bolton 1972*a*, *b*, *c;* Walborn 1973). X-ray intensity fluctuations have been observed as periodic pulse trains with "periods" of 0.3 s to 10 s, but no regular period is present (Schreier *et al.* 1971). Light curves show optical variations of the order of a few hundreths of magnitude, interpreted as due to the ellipticity of HDE 226868 and the inclination of the orbit (Cherepashuk, Lyutiy, and Sunyaev 1973). Under the assumption that the mass of the primary is consistent with its apparent spectral type, it follows, from spectroscopic as well as photometric data, that the mass of the unseen secondary is much too big to be a neutron star or a white dwarf and thus the secondary may be a black hole (Ruderman 1972; Brucato and Kristian 1973; Cherepashuk *et al.* 1973). However, models have been proposed with considerably lighter secondaries, assuming a less massive ($\sim$1 $M_{\odot}$) primary in a later evolutionary stage. Such low-mass models (Trimble, Rose, and Weber 1973; Trimble 1973; Blumenthal, Faulkner, and Kraft 1973; Greenstein 1973) differ greatly in luminosity from the highly massive models. Recent distance calculations (Bregman *et al.* 1973; Margon, Bowyer, and Stone 1973) seem to rule out the possibility of a low-mass model for Cyg X-1.

It has been found, from spectroscopic studies, that the absorption-line spectrum of the primary (visible star) is entirely normal, but a peculiar, variable emission line at the position of He II λ4686 has been reported (Bolton 1972*b*, *c;* Brucato and Kristian 1972; Smith *et al.* 1973; Walborn 1973). Hutchings *et al.* (1973) have found that this He II λ4686 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}. A possible explanation for the origin of this line is given by Hutchings *et al.* (1973), who assume that the line might be emitted by a jet of matter flowing from the primary to the secondary star. This, however, is only a qualitative explanation.

In what follows, we shall discuss two types of models. It is found that only one of them can quantitatively explain the observations of Hutchings *et al.* (1973). Both models are built under the assumption that the primary star fills its Roche lobe and that matter is flowing from the inner Lagrangian point toward the compact secondary. However, this jet does not fall directly upon the secondary but forms a disk of matter around it (strictly speaking, the presence of this disk is not necessary for model I). If the secondary is a black hole, then accretion of matter from the inner part of the disk into the black hole provides a suitable source of X-rays (Shakura and Sunyaev 1973).

II. THEORETICAL APPROACH

In what follows we shall refer to the visible star as the "primary" and to the unseen companion as the "secondary." The eccentricity of the system is $e = 0.14$ (Bolton 1972*a*). Since it is very small, we shall assume $e = 0$ in what follows. Thus, our equations may be referred to a corotating frame of reference with its origin at the center of mass of the system. We will use dimensionless quantities, unless otherwise stated. The units of mass, time, and length are, respectively, the total mass of the system $M_p + M_s$, the inverse of its angular velocity Ω, and the distance L between the centers of mass of the two objects (e.g., Szebehely 1967). For instance, if we take for the period of the system the observed value of 5.6 days, the units of length and velocity (in solar radii and km s^{-1}, respectively) turn out to be

$$[l] = 13\left(\frac{M_p/M_\odot}{1-\mu}\right)^{1/3}$$

and

$$[v] = 120\left(\frac{M_p/M_\odot}{1-\mu}\right)^{1/3},$$

where

$$\mu = \frac{M_s}{M_p + M_s}.$$

These quantities depend very slightly on M_p and μ. If the mass of the primary is taken as $M_p \sim 30\ M_\odot$ (typical mass of an OB Iab star), then 380 km s^{-1} $< [v] <$ 470 km s^{-1} and 41 $R_\odot < [l] <$ 50 $R_\odot$ for $0.1 < \mu < 0.5$. By using the dimensionless quantities of the restricted three-body problem, it can easily be shown that the radial velocity of any material point with synodic coordinates x,y, as seen by a fixed observer, is

$$V = -\sin i \sin(t+\phi)[(\dot{x}-y)^2 + (\dot{y}+x)^2]^{1/2}. \quad (1)$$

In this expression, the dots represent time derivatives, t is time, the angle i is the orbital inclination, and ϕ is defined by

$$\dot{x} = y - \sin\phi[(\dot{x}-y)^2 + (\dot{y}+x)^2]^{1/2}, \quad (2a)$$

$$\dot{y} = -x + \cos\phi[(\dot{x}-y)^2 + (\dot{y}+x)^2]^{1/2}. \quad (2b)$$

In particular, for a primary with $x = \mu$, $y = \dot{x} = \dot{y} = 0$,

$$V_{\rm prim} = -\mu \sin i \sin t. \quad (3)$$

This identifies ϕ as the phase angle of the material point with respect to the primary (assuming that the primary is spherically symmetric, we can think of radiation as coming to the observer from its center of mass). Furthermore, the ratio R of the amplitudes of the observed radial velocities, given by equations (1) and (3), is the dimensionless number

$$R = \frac{[(\dot{x}-y)^2 + (\dot{y}+x)^2]^{1/2}}{\mu}, \quad (4)$$

which is independent of i.

III. COMPUTATIONS AND RESULTS

a) *Model I*

According to this model, the He II λ4686 line is emitted by some "point" in the jet. As long as the matter leaving the Lagrangian point does not reach the disk, it will move as in free fall and it is possible to consider each point in the jet as a free particle moving in a trajectory described by the restricted three-body problem. Calculations made *a posteriori* showed that a hydrodynamical treatment is not necessary for the jet, because the work done by pressure along the jet is negligible compared with the work done by the gravitational force. We assume that the value of the outflow velocity from the Lagrangian point is of the order of magnitude of the thermal velocity of particles in the stellar atmosphere. This is a good approximation if the rotational velocity of the primary is negligible, as is usually the case (Kopal 1956). In this case, the trajectory of the particles depends very weakly on the direction and magnitude of the initial velocity (Kuiper 1941).

The equations for the trajectory of the jet can be solved numerically. Thus, for a given value of μ, every point in the jet will give a definite velocity ratio R and a phase ϕ. In figure 1, a ($\tan\phi$, R)-diagram is shown, where we have plotted these values for trajectories of particles with initial velocities (-0.1, -0.1), (-0.1, 0), and (-0.1, 0.1), for different values of μ. It can be seen that the best fit to the data of Hutchings *et al.* (1973) is obtained for $\mu \sim 0.3$, although somewhat greater values could be possible due to the uncertainty in the data.

In any case, it is clear from figure 1 that $0.25 < \mu < 0.45$. This, together with the value 70 km s^{-1} for the velocity amplitude of the primary, implies that the mass of the secondary must be $1\ M_\odot/\sin^3 i < M_s < 3.2\ M_\odot/\sin^3 i$; on the other hand, if we assume for the primary a mass of $M_p \sim 30\ M_\odot$ (in accordance with its spectral type and luminosity class), we get for the secondary a mass of $10\ M_\odot < M_s < 25\ M_\odot$. The point of emission in the jet is located at a distance of about $0.12L$ from the Lagrangian point, for $\mu = 0.3$ (this distance is about $0.08L$ and $0.2L$ for $\mu = 0.25$ and $\mu = 0.45$, respectively).

b) *Model II*

According to this model, the He II λ4686 line is radiated by the disk around the secondary in the region where the jet impacts the disk. The basic assumption that has been made is that the border of the disk rotates with Keplerian velocity, with respect to a nonrotating frame of reference (Thorne and Novikov 1973; Shakura and Sunyaev 1973). The validity of this assumption is supported by numerical calculations, which show that a Keplerian circular orbit is a good approximation for the solution of the restricted three-body problem. This holds valid even for orbits with a radius as large as $\frac{3}{4}$ of the Roche lobe radius.

Let us suppose that the jet impacts the border of the disk at a point located at a distance r from the secondary. If this point has a Keplerian velocity $(\mu/r)^{1/2} - r$ (in the corotating frame), then it can be shown that

$$r = \frac{\mu}{(\mu R\sin\phi)^2 + (1-\mu+\mu R\cos\phi)^2} \quad (5)$$

for a point radiating in such a way that the phase of the emitted line is ϕ and the velocity ratio with respect to

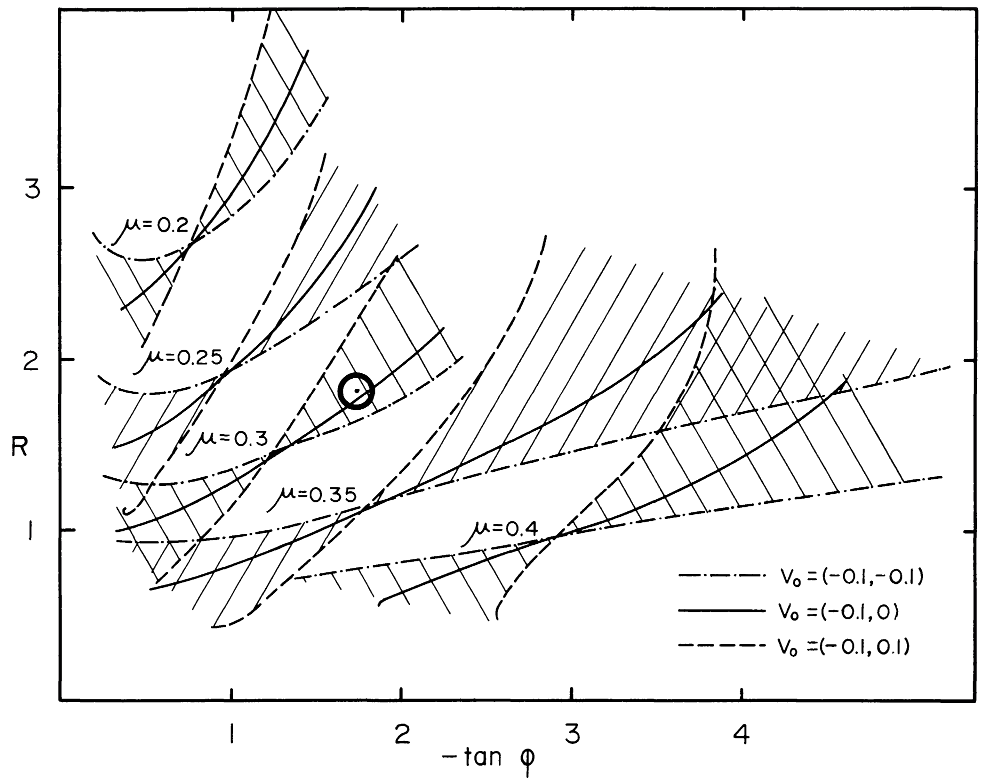

FIG. 1.—The allowed phase angle ϕ and velocity ratio R for different values of μ along trajectories of particles leaving the Lagrangian point with initial velocities $(-0.1, -0.1)$, $(-0.1, 0)$, and $(-0.1, 0.1)$. Trajectories with smaller initial velocities will give points located in the shaded regions. The circle represents the data given by Hutchings *et al.*

the primary is R. Obviously r must be located within the Roche lobe, for the model to have any physical meaning. From equation (5), it can be seen that for $\phi = 120°$ and $R = 1.8$, r lies inside the Roche lobe only for $\mu \leq 0.17$. For the upper limit $\mu = 0.17$, r would be equal to the distance between the secondary and the inner Lagrangian point.

We thus conclude that this model is consistent only for $\mu < 0.17$. Now, a period of 5.6 days and a velocity amplitude of 70 km s^{-1} imply that, for $\mu < 0.17$, $M_p > 35\ M_\odot/\sin^3 i$ and $M_s > 7\ M_\odot/\sin^3 i$. These results give highly unrealistic values for the mass of the primary if $i \sim 30°$, which is the value obtained by Hutchings *et al.* (1973).

IV. CONCLUSIONS

a) According to model I, the emission of the He II λ4686 line by the jet of matter that goes from the primary to the secondary is perfectly compatible with the observational data of Hutchings *et al.* for $\mu \sim 0.3$. (Hutchings *et al.* derive a value of $\mu \sim 0.4$, from other considerations.) This in turn means that, if $M_p = 30\ M_\odot$, the mass of the secondary compact companion should be $10\ M_\odot < M_s < 25\ M_\odot$, which is too large for a white dwarf or a neutron star, and thus it may be a black hole. The problem of the physical conditions under which the He II λ4686 line arises remains open.

b) The emission of the line He II λ4686 by a disk rotating with Keplerian velocity is very unlikely, because of the unrealistic mass obtained for the primary ($M_p > 35\ M_\odot/\sin^3 i$). However, the question remains open for a disk that does not rotate with Keplerian velocity.

c) A third model could be one in which the primary is radiating the He II λ4686 line, due to a reflection effect. However, in this case, from formula (2) and the data of Hutchings *et al.*, quite unrealistic values for the velocity at the point of emission would follow ($\dot{x} \simeq -0.7$, that is, $\sim$300 km $^{-1}$ directed toward the secondary).

We are indebted to the IBM Scientific Center of Latin America for computational facilities, and to Dr. E. E. Mendoza V. for his assistance in programming.

REFERENCES

Bolton, C. T. 1972*a*, *Nature*, **235**, 271.
———. 1972*b*, *IAU Circ.*, *No.* 2624.
———. 1972*c*, *Nature Phys. Sci.*, **240**, 124.
Blumenthal, G., Faulkner, J., and Kraft, R. 1973, remarks before the Kitt Peak X-ray Astronomy Conference, Tucson, Arizona, March 5–8.
Bregman, J., Butler, D., Kemper, E., Koski, A., Kraft, R. P., and Stone, R. P. S. 1973, *Ap. J.* (*Letters*), **185**, L117.
Brucato, R. J., and Kristian, J. 1972, *IAU Circ.*, No. 2421.
———. 1973, *Ap. J.* (*Letters*), **179**, L129.
Cherepashuk, A. M., Lyutiy, V. M., and Sunyaev, R. A. 1973, *Astr. Zh.*, **50**, 3.
Greenstein, J. L. 1973, *Astr. and Ap.*, **23**, 1.
Hutchings, J. B., Crampton, D., Glaspey, J., and Walker, G. A. H. 1973, *Ap. J.*, **182**, 549.
Kopal, Z. 1956, *Ann. d'Ap.*, **19**, 298.
Kuiper, G. P. 1941, *Ap. J.*, **93**, 133.
Margon, B., Bowyer, S., and Stone, R. P. S. 1973, *Ap. J.* (*Letters*), **185**, L113.
Ruderman, M. 1972, *Ann. Rev. Astr. and Ap.*, **10**, 427.
Schreier, E., Gursky, H., Kellogg, E., Tananbaum, H., and Giacconi, R. 1971, *Ap. J.* (*Letters*), **170**, L21.
Shakura, N. I., and Sunyaev, R. A. 1973, *Astr. and Ap.*, **24**, 337.
Smith, H. E., Margon, B., Conti, S. 1973, *Ap. J.* (*Letters*), **179**, L125.
Szebehely, V. 1967, *Theory of Orbits* (New York and London: Academic Press).
Tananbaum, H., Gursky, H., Kellogg, E., Giacconi, R., and Jones, C. 1972, *Ap. J.* (*Letters*), **177**, L5.
Thorne, K. S., and Novikov, I. 1973, in *Black Holes*, Les Houches, 1973.
Trimble, V. 1973, *Astr. and Ap.*, **23**, 281.
Trimble, V., Rose, W., and Weber J. 1973, *M.N.R.A.S.*, **162**, 1P.
Walborn, N. 1973, *Ap. J.* (*Letters*), **179**, L123.
Webster, B. L., and Murdin, P. 1972, *Nature*, **235**, 37.