BEHAVIOR OF MATTER NEAR THE OUTER REGION OF THE ACCRETION DISK IN HER X-1

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ABSTRACT. Detailed analysis of numerous observational data for Her X-1 / HZ Her shows that Her X-1 has a rare type of accretion regime: impulses of mass transfer every 0.81 d. Semi-empirical analysis show complicated 3 D type of gas flow near the outer disk rim of Her X-1: interaction of gas stream with disk forms blobs, which are disintegrated into small drops of matter ("sprays") by an interaction with gaseous corona around the outer disk rim. Fall of the sprays on different parts of the disk decreases time of accreting mass flow along disk radius. Evaporation of sprays is a source of mass supporting the disk corona. The corona and disintegrated blobs (sprays) have numerous observational manifestations in optical and X-ray ranges. Evaporation of the corona from the Roche lobe could be an important source of orbital angular momentum loss and, consequently, a source of orbital period variation.

1. INTRODUCTION

Her X-1/HZ Her has been observationally studied in many details and shows many features of X-ray and optical light curves: X-ray dips (Crosa & Boynton, 1980), flickering of flux in the dips (Vrtilek & Halpern, 1985; Voges et al., 1985), and several types of fine details of optical light curves and polarization (Karitskaya et al., 1986 and references within; Bochkarev & Karitskaya, 1989). Crosa & Boynton's (1980) "clock" mechanism of mass transfer in Her X-1 every $P_d = (P_{1.7}^{-1} + P_{35}^{-1})^{-1}/2 = 0.81$ d ($P_{1.7}$ and P_{35} stand, respectively, for orbital and precession periods) is confirmed spectoscopically in optics (Hutchings & Crempton, 1977), UV (Howard & Wilson, 1983 b), by analysis the 1.24-s pulsations (Middleditch, 1983) (see discussion in papers by Karitskaya et al., 1986, Bochkarev & Karitskaya, 1989), and by analysis of features of optical light curve.

2. MASS TRANSFER

Accretion disk of Her X-1 is inclined to the orbital plane and has a precession type movement (e.g. Howard & Wilson, 1983 a). The X-ray

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pressure to the X-ray heated side of the star in Her X-1, $\log P_x \approx 3.6$, is greater than the internal (gas and radiation) pressure, $\log P \approx 3.4$, in the atmosphere (Bochkarev & Karitskaya, 1986, 1989). Therefore every $P_d = 0.81$ d in entering the disk shadow the external pressure is cut-off and rarefaction wave may throw a gas away from the star. Four hours later the gas reaches outer disk rim (Fig. 1).

Thermal explosion resulting from interaction of the gas stream with the accretion disk scatters accreting gas into all directions forming a blob. Rayleigh-Taylor type instability of the blob expanding into corona around the outer disk rim disintegrates it into small drops (sprays) on a timescale of a few hours (Bochkarev & Karitskaya 1986, 1989), Fig.2. Spray parameters following from UV spectral data (Howard & Wilson, 1983 b) and X-ray flickering during X-ray dips are the following: number density $n \approx 4\ 10^{13}$ cm^{-3}, $T \approx 30000$ K, initial size $\approx 10^{10}$ cm. The size is decreased by Rayleigh-Taylor instability on timescale about a few hours (Bochkarev & Karitskaya 1986, 1989). The smallest sprays are evaporated effectively. The large ones are protected against expansion by the pressure of the corona. Each blob exists about 20 h.

Each spray moves along an individual Keplerian orbit around the disk. Cloud of sprays (blob) obscures time-to-time the X-ray source in the center of the disk producing X-ray dips (Fig.2). Absorption by individual sprays with column density $N \approx 10^{23-24}$ cm^{-2} makes a flickering of X-ray flux during dips which has been observed by EINSTEIN (Vrtilek & Halpern, 1985) and EXOSAT (Voges et al., 1985).

After a half of the first orbital period (about 5 h after formation) a part of sprays falls onto the accretion disk surface (Fig.2). Peculiar velocities of sprays are about 200 km/s (Bochkarev & Karitskaya, 1989), which is close to the orbital velocity of the outer disk rim ($\simeq$ 250 km/s). Therefore a part of sprays reaches disk surface far from the outer rim. It is an effective mechanizm of mass transfer along disk radius (for outer half of the disk).

3. GASEOUS CORONA AROUND OUTER PARTS OF ACCRETION DISK

The blob sprays are protected against fast (τ = 1000 s) evaporation into vacuum by the equilibrium of pressures inside the sprays and in surrounding gas (Bochkarev & Karitskaya, 1986, 1989). It corresponds to corona parameters $n \approx (5-7)\ 10^{11}$ cm^{-3}, $T \approx (2-2.5)\ 10^6$ K (Fig.3). The coronal gas is approximately corotated to the disk. Detailed calculation of heat and ionization balance (Bochkarev 1989, 1991) has shown that such a corona reaches an equilibrium in the field of the X-ray emission of the neutron star. Argon, calcium, and iron are ionized up to hydrogen-like and He-like ions and the lighter elements - up to the bare nuclei. The main source of mass of the corona can be evaporation of the smallest sprays.

Characteristics of the corona are the following: column density is $N \approx 1.5\ 10^{23}$ cm^{-2}, Thompson optical depth $\tau_T \sim 0.1$, volume emission measure $NV \simeq 10^{58}$ cm^{-3}, mass $\approx 10^{22}$ g. Bochkarev (1989) discussed in detail several observational evidences of the corona: scattering of the neutron

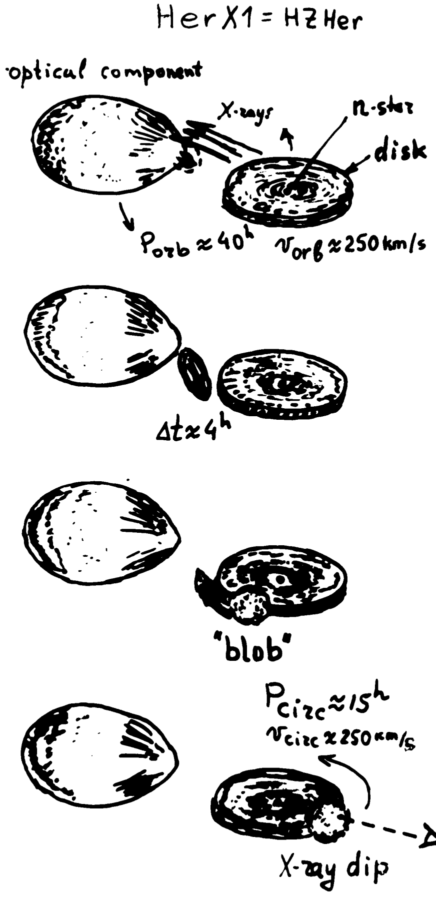

Fig. 1. A scheme of impulsive mass tranfer in Her X-1

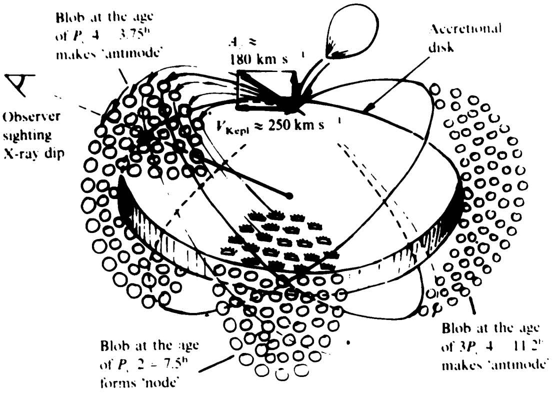

Fig. 2. A scheme explaning the developement of a blob. The accretion disk is depicted. The star is behind the disk. A portion of transferred matter hits the edge, disintegtates into drops (sprays), and, in $P_c/4$ = 3.75 h (P_c is a period of blob circulation around the disk according Crosa & Boynton, 1980) forms a "swell or antinode", i.e., a cloud of drops spaced strongly apart in the direction perpendicular to the disk plane. This is the most favorable moment for an X-ray dip to occur. After a half of the period of rotation around the disk the blob particles converge mainly in the disk plane. A fraction of sprays falls onto the disk surface, whereas the remaining drops form a next swell in another $P_c/4$ hours, etc.

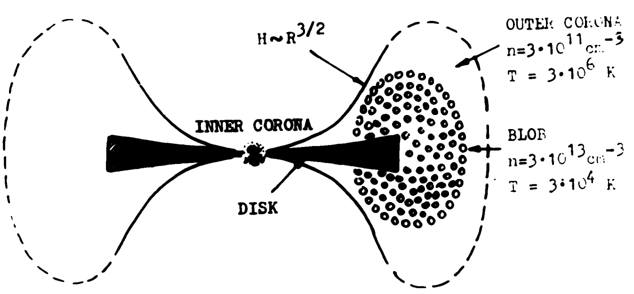

Fig. 3. A scheme explaning the position of hot corona around the outer regions of the accretion disk and a sprayed blob

star X-ray emission by the corona produces a X-ray flux during 35-d phases "OFF" ($L_x^{OFF} = (0.03 \div 0.05)\ L_x^{ON}$); smoothed X-ray eclipse ingress and egress during phases OFF; a part of Fe-line (6-7 keV) emission in the OFF phases; decreasing of X-ray modulation with $P_x = 1.24$ s during the OFF phases. Thermal emission of the corona is a source of excess of Her X-1 soft X-ray emission during eclipses in the OFF phases.

Thermal evaporation of the coronal gas from the n-star Roche lobe can be an important source of mass loss by the corona and by Her X-1 as a whole. Bochkarev et al. (1989) discussed in detail observational evidences of the gas evaporated from the corona. A part of this gas collected near back (cold) side of the optical component has temperature $T \simeq 6000$ K. The gas produces long-term (>1000 d) variations of HZ Her colours in the minima of orbital light curve ($P = 1.7$ d), which correlate with variations of the n-star rotational period $P_x = 1.24$ s, i.e. with intensity of accretion. If the evaporation from the conona makes a mass flux comparable with accretion mass flux onto n-star ($\dot{M} \simeq 10^{-8}\ M_\odot$/yr), the evaporation can be an important mechanism of orbital momentum loss and give an observable decrease of HZ Her orbital period $\dot{P}/P \simeq 10^{-8}$. Such variations have been found by Boynton et al. (1991): $\dot{P}/P = (-1.28 \pm 0.13)\ 10^{-8}$.

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