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Mechanism of Mass Flow from Upsilon Sagittarii

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Abstract

To explain the displaced Hα absorption line which appears periodically in the spectrum of Upsilon Sagittarii, the supersonic flow from the stellar corona which starts around the Lagrangian point and extends to a cone in the vicinity of the secondary is discussed. From the observed velocity of -300 km/s, the temperature of the corona of the primary is estimated to be about $3.8 \cdot 10^6$°K. With our model, we can explain the observed duration of 40 days of Hα absorption if the mass of the primary is less than the mass of the secondary. Applications to other stars that are known to be ejecting mass are also discussed.

1. *Introduction*

The hydrogen-deficient star Upsilon Sagittarii is known to be a single-lined spectroscopic binary. Its orbit was determined by WILSON (1914) and his orbit has represented later observations very well (PLASKETT 1927, 1928; GREENSTEIN and ADAMS 1947; HACK 1960). The orbital elements by WILSON (1914) are shown in Table 1.

TABLE 1. Orbital Elements for Upsilon Sagittarii by Wilson (1914).

Period	137.939 ± 0.017 days
Eccentricity	0.087 ± 0.016
Angle of Periastron	$28.6° \pm 2.8°$
Periastron Passage	JD 2419648.72 ± 1.15
Velocity of the System	$+12.1$ km/s
Semiamplitude	48.15 km/s
$a \sin i$	$9.101 \cdot 10^7$ km
Mass function	$1.582\ M_\odot$.

The spectrum of this star was analyzed by many investigators: MORGAN (1934); GREENSTEIN (1940, 1943, 1950); GREENSTEIN and MERRILL (1946); GREENSTEIN and ADAMS (1947); HACK (1960); and HACK and PASINETTI (1963). According to the most recent analysis by HACK and PASINETTI (1963), the hydrogen to helium ratio is about 1: 200.

Although hydrogen is deficient in the atmosphere of this star, Hα is observed in undisplaced strong emission. Hα is also observed occasionally in displaced absorption which corresponds to -300 km/s: CAMPBELL (1895); CANNON (1912); MERRILL (1913a, b, 1944); GREENSTEIN (1943); GREENSTEIN and MERRILL (1946);

BIDELMAN (1949); and HACK (1960). Emission lines of other elements are also reported: Ca II (WEAVER 1943); Ca II and [Ca II] (MERRILL 1943, 1944); Ca II, [Ca II], and Fe II (GREENSTEIN and MERRILL 1946).

A gaseous envelope and a jet stream are supposed to be the origins of the emission and the displaced absorption of Hα, respectively. However, the mechanism of the formation of such an envelope and a jet has not been studied yet. The purpose of the present study is to suggest a mechanism which could explain the peculiar changes of the displaced absorption line.

2. *Summary of the Observational Results*

Many investigators have reported that the displaced Hα absorption line appears during an interval of about 40 days centered about the phase 20 days at which the primary is farthest from us (e.g. BIDELMAN 1949, HACK 1960). In order to make sure of this fact, we have plotted in Figure 1 all the observations on Hα absorption that have ever been published. The abscissa is the phase by WILSON (1914) and the ordinate is the central intensity of Hα absorption. HACK (1960) gave the profiles of Hα. In Figure 1, we represented her observations by crosses. As the other observers reported only qualitatively, $r_c=1.0$ was assigned when they described the line as "strong" and $r_c=0.0$ when they described the line as "absent". We obtained several spectrograms with the coudé spectrograph attached to the 188 cm reflector at Okayama. In Figure 1, open circles

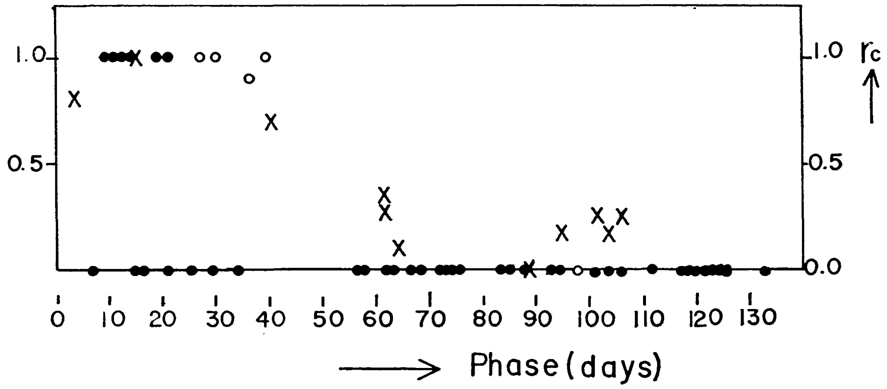

FIG. 1. Correlation between the violet-shifted Hα line and phase of the orbital period.
cross: HACK (1960), open circle: present investigation, dot: others.

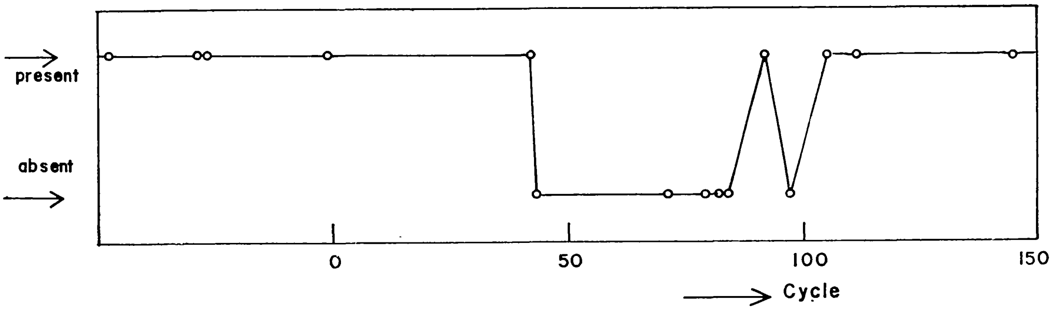

FIG. 2. Changes in the line intensity of displaced Hα absorption.

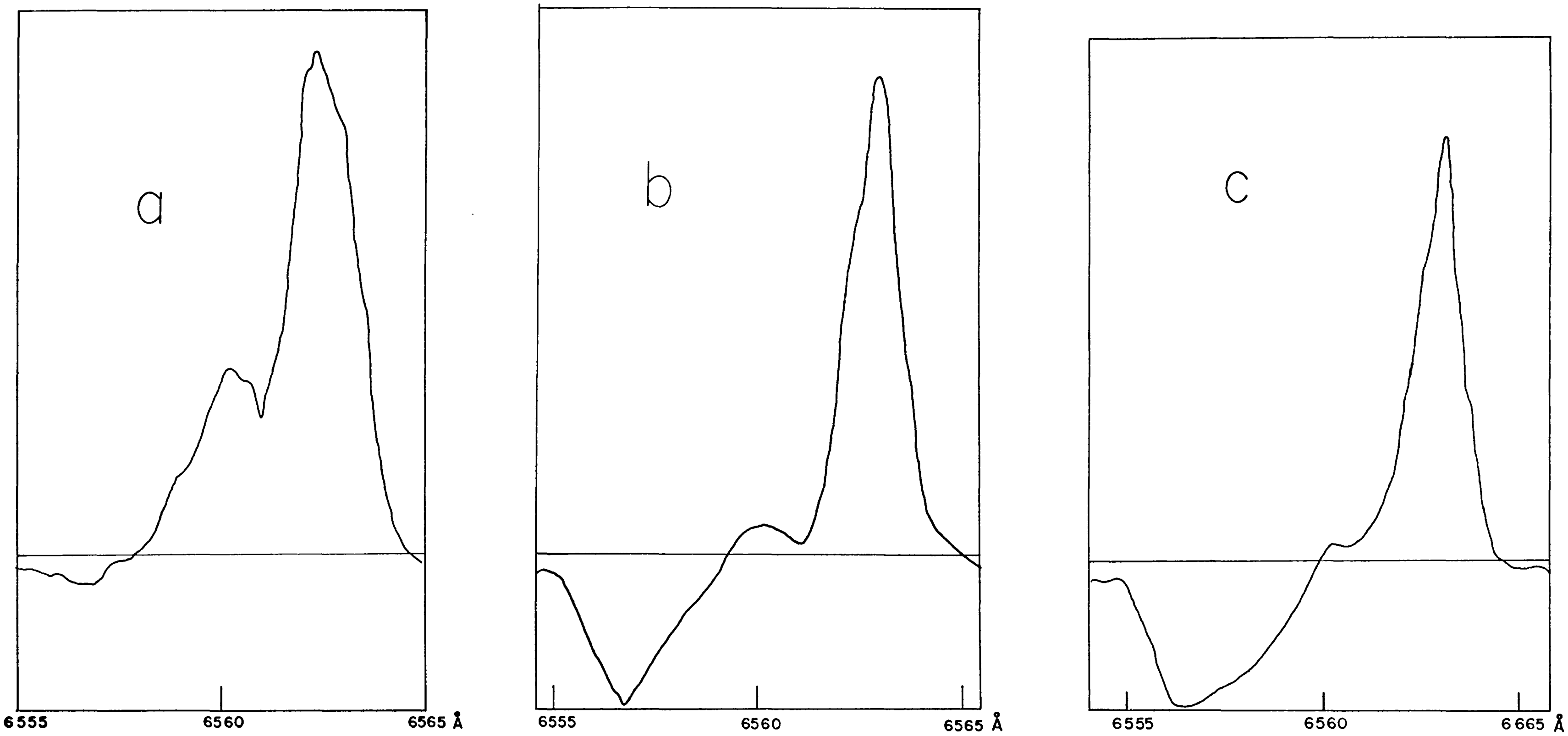

FIG. 3. a. Microphotometer tracings of the emission and absorption features of Hα. a. C4-1701. Phase 98 days. Out of Hα eclipse.

b. Average profile of C4-1722 and C4-1725. Phase 14 days. Middle of Hα eclipse.

c. Average profile of C4-1733 and C4-1747. Phase 37 days. End of the Hα eclipse.

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TABLE 2. Journal of Observations.

Plate Number	Date	Phase	Emulsion
C4-1701	April 29, 1967	98	103a-F
C4-1722	June 21, 1967	13	103a-F
C4-1725	June 23, 1967	15	103a-F
C4-1733	July 14, 1967	36	103a-F
C4-1747	July 17, 1967	39	103a-F

represent our observations. Data on our spectrograms are given in Table 2.

From Figure 1, it is evident that the strong displaced absorption line ($r_c>0.5$) appears only at the phases from 0 to 40 days. As the orbital period is 138 days, the duration of the absorption line of 40 days means that the gas flow extends to a cone whose vertical angle is more than 90 degrees. The angle of the cone plays an important role in the theory of the flow, however, it cannot be precisely determined from Figure 1 because the observations are scarce at phases 130-5 and 40-55 days when the appearance of the displaced Hα absorption starts and ends, respectively. We plan to determine the angle of the cone precisely in the next observable season.

When we see the star at 6556 A which corresponds to Hα displaced for the jet velocity of -300 km/s, the star is eclipsed by the jet stream during the phases 0 to 40 days. Therefore, we call this phenomenon as "Hα eclipse" in the later sections of this paper.

Although it seems that the eclipse character of the displaced Hα absorption in established, several plots in Figure 1 show that there was no absorption during the phases when the absorption line should appear. We have plotted observations during phases 0 to 40 days in Figure 2. The abscissa is the number of cycles by WILSON (1914) and the ordinate is 1.0 when the line was observed and 0.0 when not. Figure 2 shows that gas flow was not observed during cycles 43 to 98 with one exception in cycle 92. It is suggested that the jet appears periodically although we cannot determine the period of the "stellar cycle" of Upsilon Sagittarii because we have probably not experienced the whole cycle in spite of the accumulation of observations since 1895.

We reproduced three profiles in Figure 3. They correspond to phases 98, 14, and 37 days. It is noted that the absorption profile in Figure 3b (phase 14 days) is symmetric while that in Figure 3c (phase 37 days) is asymmetric. Such a change can also be seen in HACK's paper (1960). As the observations are scarce, we will discuss this change in the profile of the displaced Hα absorption when we obtain more data about it.

3. *Hydrodynamic Equations of Mass Flow*

In the later sections of this paper, we will discuss a possible mechanism which could explain the jet stream which extends to a cone whose vertical angle is more than 90 degrees. To interpret the observations, we assume that the displaced absorption of Hα is formed in a supersonic jet which has its origin in the corona of the primary and extends to a cone as is shown in Figure 4.

In the corona of a single star, the balance between pressure and gravity

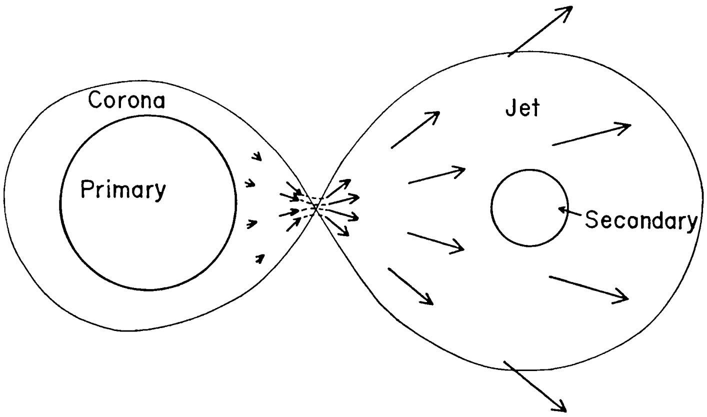

FIG. 4. A schematic figure of the flow.

determine the density distribution. At the Lagrangian point of a binary, however, there is no gravitational force that serves to balance the pressure of the corona. Therefore, the gas of corona flows into the domain of the secondary. To simplify the problem, we assume that the corona is composed of perfect monoatomic gas. As the orbital velocity of the visible component of Upsilon Sagittarii is 48 km/s, the observed velocity of −300 km/s is supposed to be much greater than the velocity of escape if we assume that the extent of the absorbing gas is comparable to the major axis of the orbit. Then, we can disregard the gravitational energy when compared to the translational energy of the jet motion. In our discussions, we tentatively assume that the Lagrangian surface is the boundary surface of the flow in the vicinity of the Lagrangian point. Whether such an assumption can be valid or not will be discussed in section 5.

With the above assumptions, our problem can be treated as a case of de Laval nozzle. We assume also that the flow is steady and isentropic, and that its speed q, density ρ, and pressure p take the same values on a plane which is perpendicular to the streamlines. Then the equation of continuity can be written in the form

$$A\rho q=F\,, \tag{1}$$

where A is the area of the cross section of the flow intercepted by the boundary surface and F the rate of mass flow crossing this area per unit time. Further, we assume that the flow is irrotational. This assumption will be discussed in section 4. Then the only additional equations needed to determine the flow are the adiabatic relation

$$p\rho^{-\gamma}=\text{constant} \tag{2}$$

and Bernoulli's law

$$\mu^2q^2+(1-\mu^2)c^2=c_*^2 \tag{3}$$

which can be deduced from the original form

$$q^2+2c^2/(\gamma-1)=\hat{q}^2 \tag{4}$$

where 0.5 $\hat{q}^2$ is the Bernoulli constant, introducing μ instead of γ

$$\mu^2=(\gamma-1)/(\gamma+1) \tag{5}$$

and a quantity c_* with the dimensions of velocity,

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$$c_*=\mu\hat{q}\ . \tag{6}$$

The sound velocity of perfect gas is given by

$$c^2=\gamma p/\rho=\gamma RT/\bar{\mu} \tag{7}$$

with $\gamma=5/3$ for monoatomic gas and $\bar{\mu}$ the molecular weight.

It is known that equations (1), (2) and (3) permit two types of solutions: *i.e.* supersonic and subsonic ones. We derive from equations (1), (2) and (3) the relations

$$dA/A+d\rho/\rho+dq/q=0\ , \tag{8}$$

$$d\rho/\rho=(2/(\gamma-1))dc/c=(1-\mu^2)/\mu^2\cdot dc/c\ , \tag{9}$$

and

$$\mu^2 qdq+(1-\mu^2)cdc=0\ ; \tag{10}$$

hence we find

$$dA/A=((q^2/c^2)-1)dq/q\ . \tag{11}$$

The last equation shows that for increasing area A, the speed q increases when $q>c$ and decreases when $q>c$, therefore, changes between supersonic and subsonic flows cannot take place if the boundary is a single cone. Transition from subsonic to supersonic flow becomes possible, however in a de Laval nozzle. A de Laval nozzle consists of two sections of cones or similarly-shaped tubes with the same axis and placed opposite each other. In our problem, the Lagrangian surface near the Lagrangian point forms the boundary of a de Laval nozzle.

In the de Laval nozzle, flow which is subsonic in the entry section, passing through the throat, can change into supersonic in the exhaust section. Whether this is realized or not depends on the pressure in the domain beyond the exhaust section. In the case of our model, if the secondary has a dense corona, the flow can not change into supersonic. Therefore, in the system of Upsilon Sagittarii, it is supposed that only the primary has a corona.

In what follows, the suffix $_*$ denotes values at the throat. Then equations (1), (2) and (3) may be written in the following form, in which c/c_*, ρ/ρ_*, p/p_*, A/A_* are expressed in terms of $q/q_*=q/c_*$ or c/c_*:

$$(c/c_*)^2=(1-\mu^2)^{-1}(1-\mu^2(q/q_*)^2)\ , \tag{12}$$

$$\rho/\rho_*=(c/c_*)^{2/(\gamma-1)}\ , \tag{13}$$

$$p/p_*=(c/c_*)^{2\gamma/(\gamma-1)}\ , \tag{14}$$

$$A/A_*=(c/c_*)^{-2/(\gamma-1)}(q/q_*)^{-1}\ . \tag{15}$$

For more exact treatment of the flow, see, for example, the textbook by COURANT and FRIEDRICHS (1948).

4. *State of Corona and Flow*

From the observed velocity of -300 km/s, we estimate the temperature of corona. As we assume the gas is monoatomic, γ is 5/3 and μ is 1/2. At infinity, the left side of the equation (12) is zero, therefore

$$c_*=q_*=\mu\hat{q}=0.5\times 300\ \mathrm{km/s}=150\ \mathrm{km/s}\ . \tag{16}$$

We assume the velocity of flow at the bottom of the corona is zero. Then

$$c=c_*/(1-\mu^2)=200\ \mathrm{km/s}\ . \tag{17}$$

Thus the temperature of the corona is

$$T=\bar{\mu}c^2/\gamma R=3.8\cdot 10^6\ ^\circ\mathrm{K}\ , \tag{18}$$

and the temperature at the throat is

$$T_*=\bar{\mu}{c_*}^2/\gamma R=2.1\cdot 10^6\ ^\circ\mathrm{K}\ . \tag{19}$$

We estimate the extent of the flow near the Lagrangian point. When the distance from the throat is sufficiently large, the velocity q is almost q_*/μ. From equations (15) and (7), we obtain

$$A/A_*=\mu(T/T_*)^{-1/(\gamma-1)}\ . \tag{20}$$

We assume that the hydrogen gas which absorbs the Hα line fills the Lagrangian surface and its temperature is about 10^4 °K. We may estimate that the distance from the secondary to the Lagrangian surface is 0.5 a. If $\sin i$ is nearly equal to unity, then

$$A=\pi(5\cdot 10^7\ \mathrm{km})^2 \tag{21}$$

and the radius of the flow near the Lagrangian point is

$$r_*=5\cdot 10^7\mu^{-1/2}(T/T_*)^{1/2(\gamma-1)}\ \mathrm{km}=2\cdot 10^6\ \mathrm{km}\ . \tag{22}$$

In what follows, we discuss the condition on which the flow is laminar. Turbulent motion occurs when the Reynolds number is greater than 10^3. The Reynolds number is

$$Re=vl/c\lambda\ , \tag{23}$$

where v is the velocity of the flow, l the size, c the sound velocity, and λ the mean free path,

$$\lambda=(9/4\pi)(k^2T^2/Ze^4N)=1.29\cdot 10^5\ T^2/N\ . \tag{24}$$

The condition that the flow is laminar at the throat is obtained with the help of the equations (19), (22), (23) and (24) and the relation that $v=c$ at the throat. This gives an upper limit of the density,

$$N<3\cdot 10^9\ . \tag{25}$$

The Reynolds number becomes large with the distance from the Lagrangian point. With the help of the equations (7), (12), (13), (15) and (24), we obtain

$$Re/Re_*\fallingdotseq(c/c_*)^{-3.5}\ . \tag{26}$$

Therefore, our treatment of the flow is valid for the region where $c/c_*>0.1$ if the Reynolds number at the throat is of the order of unity.

5. *Conditions for the Existence of Corona*

In our discussion, we assumed that the flow has its origin in the corona of the primary star. In this section, we will discuss whether a corona can exist around the primary of Upsilon Sagittarii. The first condition is that there is a sufficient supply of energy from the photosphere to corona. Therefore, strong activities at the surface are necessary. HACK and PASINETTI (1963) derived the turbulent velocity of 13 km/s for deeper layers and 6 km/s for outer surface layers. These values seem to be sufficient for the support of the high temperture of corona.

The second condition is a relation among the mass and the radius of the star and the temperature of the corona. The density distribution in a corona can approximately be given by the hydrostatic equation, which using the Newton force in place of the constant gravity, is written as

$$-d(NkT)/dr=(GM/r^2)N\bar{\mu}m_H\ , \tag{27}$$

where the notations have their usual meanings. Further, if we assume the corona is isothermal, then

$$N=N_0\exp(GM\bar{\mu}/aRTx)\ ,\quad x>1\ , \tag{28}$$

where x is the distance from the center of the star measured in the unit of the stellar radius a. For the solar corona, the constant $(GM\bar{\mu}/aRT)$ is about 10. If this value is doubled, corona will not be able to exist and collapse to the star. Therefore, we have a relation which gives an upper limit of M/a

$$(M/M_\odot)/(a/a_\odot)\leq T/T_\odot=4\cdot10^6/1.6\cdot10^6=2.5\ . \tag{29}$$

If we could determine the diameter of the primary from the observations of the occultation at Hα, relation (29) yields the upper limit of the mass of Upsilon Sagittarii.

An explanation may be given for the assumption that the Lagrangian surface forms the boundary of the flow. If we write the equation (27) in the form

$$-d(NkT)/dr=(dU/dr)N\bar{\mu}m_H\ , \tag{30}$$

this equation is valid for the flow outside the Lagrangian surface and near the Lagrangian point as long as the velocity component of the flow perpendicular to the equipotential surface is zero. Therefore, the density decreases rapidly as the distance from the Lagrangian surface becomes large if dU/dr is large enough. Such a decrease in density has the same meaning as that there is a boundary at the Lagrangian surface. The equation (30) is not valid for the flow inside the Lagrangian surface because the flow crosses the equipotential surface.

6. *Discussions on Other Mechanisms*

In the theory of jet which we discussed in the present paper, thermal energy is converted into the translational energy. Another mechanism by which the gravitional energy is converted into translational energy is worth being discussed. In this case, the primary fills its Lagrangian surface, and the matter that is pushed out of the Lagrangian surface begins to orbit the secondary. We assume that the velocity observed at Hα is attained at a half the distance from the Lagrangian point to the secondary as the most favorable case. However, it is clear that we cannot explain the long duration of Hα eclipse with such a model.

Explosion is another candidate for the explanation of the -300 km/s component. But, as Figure 1 shows, this possibility can be easily excluded, because the periodic appearance of the displaced Hα absorption seems to be an established fact. PLASKETT (1927) reported that Hβ, Hγ, and Hδ have three components of displaced absorption lines which correspond to -150, -200 and -300 km/s. According to him, these lines appeared even at phases when the primary was in front, but GREENSTEIN (1950) criticized PLASKETT's results as misidentifications.

7. *Origin of Hα Emission and the Infrared Radiation*

Passing the domain of the secondary component, the jet stream is decelerated by the gravity of both components but continues to expand. The reduced velocity of expansion may be about 200 km/s. The widths of the emission line of Hα roughly corresponds to this value. The complex feature and the changes in Hα emission can be interpreted by the change of the jet activity with time.

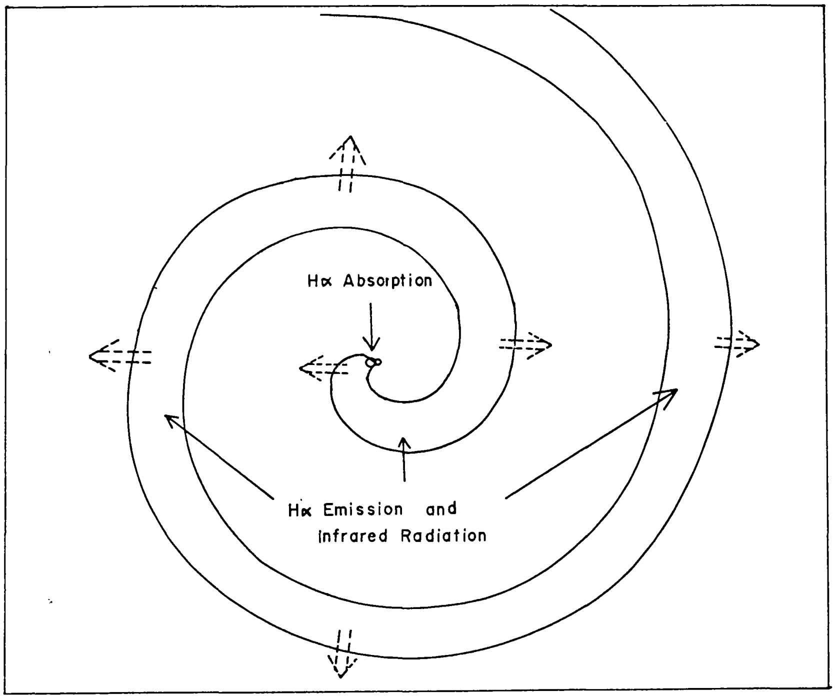

FIG. 5. A schematic large scale view of the model.

Recently, LEE and NARIAI (1967) reported abnormally strong infrared radiation from this star. They concluded that the strong infrared radiation near 3 microns must be generated in a circumstellar envelope which is very cool. With the present model, this infrared radiation can be interpreted as that from the expanding tail at about 10^8 to 10^9 km from the star.

The above two observations make the jet theory as the most favorable candidate, because with gravitational flow it is difficult to explain the stational velocity and the large Doppler velocity as are observed in Hα emission and the cool temperature as is observed in the infrared photometry.

8. *Comparisons with the Stellar Wind*

Since the time that PARKER (1958) investigated the solar wind, many studies have been done on the solar and stellar wind. For review of this problem, see WEYMANN (1963). In the theory of stellar wind, the equations that govern the flow are a little more complicated than equations (1), (2) and (3), but the characteristics of the solutions are almost the same as in the present case. The space around a single star can be represented with a cone. If the flow is wholly adiabatic, it can not change from subsonic to supersonic state. In the stellar wind, the dissipation of mechanical energy and radiation gain or loss play an important role in the change of the flow from subsonic to supersonic, while, in our theory, the shape of the Lagrangian surface makes the transition possible. The theories of stellar wind presented up to now do not discuss the dissipation of mechanical energy or energy gain or loss directly. However, they use the polytropic relation which indirectly determines the efficiency of the above mechanisms through the heat equation, because there are many uncertainties in the treatment of those mechanisms.

In the theory of stellar wind, the critical distance is determined by the mass and the radius of the star and the state of the corona. The distance is estimated to be more than two times stellar radius in most cases. In our theory, however, the critical distance is determined by the mass ratio and the distance between the two components. Therefore, in some cases, the density of the flow at the critical distance is quite large and the rate of mass loss can be larger than in the case of a single star.

9. *Mass Ejection of the Same Type Occurring in Other Stars*

A hydrogen-deficient binary HD 30353 has many similar points to Upsilon Sagittarii; the large mass function of $4.4 M_{\odot}$, a long orbital period of 360 days (HEARD 1962), a large value of turbulence of 19 km/s (NARIAI 1963), and stationary Hα emission (NARIAI 1967). The emission of Hα can be explained as in the case of Upsilon Sagittarii. NARIAI (1967) estimated the inclination of the orbit to be about 45°. If this is correct, it is possible that the displaced Hα absorption is not observed although the stationary emission is strong.

BRACHER (1967) reported that a Wolf-Rayet binary HD 211853 shows the same type of change in the profile of HeI 3889 A. But in this case the displaced absorption appears when the primary is in front. There are two possibilities in this case. The first possibility is that the corona belongs to the invisible component. But the second possibility that the flow takes place at the outer Lagrangian point seems better than the first one. In this case, the flow at the inner Lagrangian point does not occur because the invisible component has also corona and the condition for the transition of flow from subsonic to supersonic is not fulfilled. With the observed radial velocity of -1400 km/s, the temperature of the corona is estimated to be about $1.5 \cdot 10^{7}$ °K.

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