Analytical Studies on the Structure and Emission of the SS 433 Jets

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1. Introduction

The galactic source SS 433 is well known as an unique object exhibiting a jet phenomenon (for review, see Margon 1984 and Vreeland 1989). The moving behavior of Balmer and He I lines has been interpreted successfully in terms of the two opposite jets precessing with a period of 164 days. The velocity of matter outflowing in the jet is found...
to be $0.26c$ and remarkably stable, where $c$ is the speed of light. The SS 433 system is an eclipsing binary with the orbital period of 13 days. The system may consist of an early type star and an accretion disk around a compact object. The compact star may be a neutron star or a black hole, although the definite determination has been still waited.

SS 433 has attracted huge attention from the time of the discovery because of its peculiar behavior. A lot of observations have been conducted in the radio, optical and X-ray bands. Many theoretical studies have also been put forward. In spite of these enormous efforts, the most fundamental problems on SS 433 still remain unsolved. Those are the nature of the compact star and the acceleration and collimation of the jet beams.

Recently, the ASCA satellite has detected X-ray lines of various elements, such as Fe, Ni, Mg, Si, S and Ar, from the SS 433 jets (Kotani et al. 1996; Kotani et al. 1997). In the Fe case both the blue-shifted and red-shifted X-ray lines, which are emitted respectively from the approaching and receding jets, have been observed at the same time. Fitting the analytical jet model to these ASCA data, Kotani et al. (1996, 1997) have examined the properties of the X-ray emitting portion of the jet beams. They have derived important constraints on the jet parameters such as the density, temperature and size of the X-ray emitting region and the mass outflow rate. Their analyses have also implied the X-ray absorbing gas to exist in the system.

We study the structure and emission of jet beams in the X-ray emitting region and in the inner and hotter portion inside the X-ray emitting region. Based on the results on the jet structure, we discuss the acceleration mechanism for the SS 433 jets.

We present a simplified model for the SS 433 jets in section 2. We derive the analytic solutions for the structure and emission of the X-ray jets in section 3. Deriving the analytic solutions, we show that the jet structure is of two-temperature in the inner and hotter portion inside the X-ray emitting region in section 4. In the final section we discuss the appropriate jet model, the acceleration mechanism and the absorbing envelope based on our analytical results on the jet structure and emission.

2. Model

The jet may be divided into several characteristic regions depending on the distance from the central engine, the inner region, the X-ray emitting region, the optical and radio emission regions, and the outer region. Here, we focus on the X-ray emitting region and the hotter region inside of it.
No observational evidence is found for the velocity variation along the jets in SS 433. This fact implies that the matter entrainment from the ambient medium and other braking processes are unimportant in the region of our interest. Hence, we assume the matter velocity constant, \( v = 0.26c \), along the jets.

The mass outflow rate \( M_\text{jet} \) in a jet is written as

\[
M_\text{jet} = S \, v \quad ;
\]

where \( r \) is the distance from the central engine, the density and \( S \) the area of the jet cross section. For simplicity, we consider the beam shapes as expressed by

\[
S = \frac{R^2}{r^n} \quad ;
\]

where \( R \) is the radius of the jet cross section and \( n \) the constant number (Fukue 1987). In the following we examine the jet structure and emission especially for the cases of \( n = 1 \) and \( n = 2 \). The case of \( n = 2 \) corresponds to the conical beam, while the case of \( n = 1 \) to the jet beam whose cross section grows with the distance more slowly than that of the conical beam.

The matter in the jets cools, expanding and emitting radiations. Writing the temperature and radiative loss rate respectively as \( T \) and \( \dot{r} \), we have for the energy equation

\[
\frac{3}{2} \frac{k}{m_H} \frac{dT}{dr} + \frac{kT}{m_H} \frac{1}{dr} \frac{d}{dr} - \frac{v}{r} \quad ;
\]

where \( m_H \) is the mass of hydrogen, \( k \) the Boltzmann constant and the mean molecular weight of matter. The second term on the left hand side of equation (3) and the term on the right hand side represent the adiabatic and radiative coolings, respectively.

We normalize physical quantities with those at a fiducial point \( x = r_0, y = T = T_0, z = = 0 \) and \( f = = 0 \).

Here and in the following the subscript 0 is used to denote the physical quantities at \( r = r_0 \). Using these parameters, equations (1) and (3) reduce to the dimensionless equations,

\[
z = x^n \quad ;
\]

and

\[
\frac{dy}{dx} + \frac{2}{3} \frac{1}{x} y = 0 f \quad ;
\]
respectively. In equation (5) the free parameter $\zeta$ is the ratio of the ow time $t_0$ to the radiative cooling time $t_{r0}$,

$$\zeta = \frac{t_0}{t_{r0}} ;$$

(6)

where $t_0$ and $t_{r0}$ are defined respectively by

$$t_0 = \frac{x_0}{v}$$

(7)

and

$$t_{r0} = \frac{1}{2} \frac{\kappa T_0}{m_s} ;$$

(8)

Note that the ow time also expresses the adiabatic cooling time due to the plasma expansion. Equation (5) shows that the free parameter $\zeta$ determines the property of solutions and hence the thermal structure of the jet.

3. One-Temperature Jets

We consider here the region of the jet beam where a typical temperature is 10 keV and X-rays are emitted. We assume that the jet is optically thin to X-ray photons, satisfying $\chi = 0.1 R < 1$, where $\chi$ is the optical thickness and $\chi$ is the electron scattering opacity. In this region the ion-electron scattering occurs so frequently that the electrons and ions have the same temperature.

3.1. Analytic Solutions

When the radiative cooling rate is given by the thermal Bremsstrahlung emission,

$$\dot{E}_r = 5.7 \times 10^{30} \frac{P}{T} \; \text{ergs s}^{-1} ;$$

(9)

the normalized cooling rate is obtained as

$$f = z \frac{P}{y} ;$$

(10)

Equation (5) together with equations (4) and (10) can be solved analytically to yield

$$\frac{8}{x^{\frac{3}{2}} + \frac{3}{2}} \frac{1}{x^{\frac{1}{2}}} \frac{1}{x^{\frac{1}{2} - 1}} \quad \text{for } n = 1$$

$$\frac{8}{x^{\frac{3}{2}} + \frac{3}{2}} \frac{1}{x^{\frac{1}{2}}} \frac{1}{x^{\frac{1}{2} - 1}} \quad \text{for } n = 2 ;$$

(11)
Note that the solutions (11) tend to the adiabatic cooling formula, $y = 1-x^{2n}$ and $y = 1-x^{4n}$ respectively for $n = 1$ and $n = 2$, as $\theta$ approaches to zero. If we integrate the Br"{o}nss strahlung emission along the jet, we have for the X-ray luminosity emitted from the region outside the distance $x$,

$$L(x) = S_0 r_0 \int_0^\infty g(x) \text{ erg s}^{-1};$$

where

$$g(x) = \begin{cases} 
3 + \frac{3}{2} x^{-3} \frac{1}{x_{m,\text{ax}}^3} \frac{3}{2} \theta \ln \frac{x_{m,\text{ax}}}{x} & \text{for } n = 1 \\
3 + \frac{3}{2} x^{-3} \frac{1}{x_{m,\text{ax}}^3} \frac{3}{2} \% \theta \frac{1}{x} \frac{1}{x_{m,\text{ax}}} & \text{for } n = 2 
\end{cases}$$

In equation (13) $x_{m,\text{ax}}$ denotes the outer end of X-ray emitting region. As an $x_{m,\text{ax}}$ we choose here the distance beyond which the temperature drops below $0.1 \text{ keV}$.

Adopting the solution for the conical beam ($n = 2$) at $r=r_0$ 1, Kotani et al. (1996) have calculated the line X-ray emission from Fe, Ni and other elements and made the detailed comparison with the ASCA observations for SS 433. We list the standard set of jet parameters they obtained in Table 1. In Table 1, we also list the jet parameters derived from using the solution for the model with $n = 1$. The solution of $n = 1$ also reproduces well the observed properties, such as the X-ray luminosity ($10^{36} \text{ erg s}^{-1}$) and temperature ($20 \text{ keV}$). In both solutions the angular point is chosen to be the base of the X-ray emitting region of the jet. The length of the X-ray emitting region is obtained as $x_{m} = 10^3 \text{ cm}$. The optical thickness across the beam is $\% 0.1$ and hence the jet plasma in the X-ray emitting region is transparent, justifying the assumption made in the energy equation. Note that the value of the dimensionless parameter $\vartheta$ is $0.1$ or less. This fact shows that the temperature structure is determined mainly by the adiabatic cooling loss due to the plasma expansion. We notice that the kinetic energy $L_K$ carried by the outflowing matter amounts to more than $10^{39} \text{ ergs s}^{-1}$ and exceeds the Eddington luminosity for a star of one solar mass.

3.1.1. Jet inside the X-Ray Emitting Region

The jet radius $R_0$ of the X-ray emitting region and its distance $r_0$ from the central engine are at least several orders of magnitude larger than the size of the central engine that drives the jet, a neutron star or a black hole.

Although Kotani et al. (1996, 1997) have truncated the inner portion of the jet, it is quite natural to assume that
the jet beam extends more down to the vicinity of the central engine. In the following let us examine the property of the jet expected to exist inside the X-ray emitting region.

We apply the solution (11) to the inner region adjacent to the X-ray emitting region. Following equations (4) and (11), the density and temperature of the jet increase with decreasing distance. Hard X and soft gamma rays are emitted from the jet. The energy transfer from ions to electrons through the Coulomb scattering becomes less efficient at higher temperatures, whereas electrons lose energy promptly radiating X and gamma rays and expanding adiabatically. The insufficient energy transfer makes the ion and electron temperatures different at $T > 10^9$ K (see the next section for detail). The jet reaches the critical temperature $T_1 = 10^9$ K at the distance $r_1$. Here and in the following we denote the physical parameters at the innermost region of the one-temperature jet by the subscript 1.

We list the physical quantities at $r = r_1$ in Table 2. The relativistic Bremsstrahlung emission rate and adiabatic cooling rate, which are mentioned in the next section, are used to calculate $\eta$ in Table 2. The optical thickness across the beam is less than one, although approaches one, and the jet is still optically thin against electron scattering near $r = r_1$. Note that the parameter $\eta$ in the case of $n = 2$ (conical case) exceeds, though a little, one. The radiative loss as well as the adiabatic loss also contribute significantly to the plasma cooling near the innermost region of the one-temperature jet in the conical case. In the $n = 1$ case the cooling of the jet plasma is still determined by the adiabatic loss. The luminosity of X and soft gamma rays emitted from the region at $r = r_1$ is calculated from equations (12) and (13) and is listed in Table 2. In the $n = 2$ case the luminosity of soft gamma rays emitted from the region between the distances $r_1$ and $r_0$ exceeds the luminosity of X-rays ( $10^6$ ergs s$^{-1}$) emitted from the region outside the distance $r_0$ approximately by an order of magnitude, while in the $n = 1$ case the both luminosities are comparable.

4. Two-Temperature Jets

We have the two-temperature jet inside the distance $r_1$, where the ion temperature is higher than the electron temperature. Ions transfer energy to electrons through the ion-electron scattering, which in turn lose energy by the radiative emission and adiabatic expansion. The distribution of ion temperature along the jet beam can also be described by equation (3), taking $\eta = 1$ and substituting the ion energy loss rate $\dot{\epsilon}_i$ for the radiative loss rate $\dot{\epsilon}_r$. 


The ion energy loss rate $\dot{\epsilon}_i$ is given approximately by

$$\dot{\epsilon}_i = \frac{3}{2} \frac{kT}{m_H} \epsilon ;$$

(14)

where $T$ now expresses the ion temperature and $\epsilon$ is the ion-electron collision frequency. The ion-electron collision frequency is written as

$$\epsilon = 3 \times 10^2 \frac{1}{T_e^{3/2}} \text{s}^{-1} ;$$

(15)

where $T_e$ is the electron temperature.

We adopt the relativistic Bremsstrahlung emission with the Compton amplification for the radiative energy loss of electrons and approximate the emissivity by

$$\epsilon_{\text{ff}} = 4 \times 10^6 \frac{1}{T_e} \text{ergs g}^{-1} \text{s}^{-1} ;$$

(16)

where $\epsilon_{\text{ff}}$ is the Compton amplification factor. Equation (16) can be used approximately even in the optically thick case if the photon diffusion time across the jet is shorter than the flow time. Energy loss rate of electrons due to the adiabatic expansion can be approximated by

$$\dot{\epsilon}_{\text{ad}} = \frac{kT_e}{m_H} \frac{1}{t_\epsilon} ;$$

(17)

The electron temperature is determined from the balance between the energy acquired from ions and the energy lost to radiation and adiabatic expansion. When the radiative loss is dominant over the expansion loss ($\epsilon_{\text{ff}} > \epsilon_{\text{ad}}$), the electron temperature is expressed as

$$T_e = 3 \times 10^6 \frac{2^{5/2}}{T^{2/5}} \text{K} ;$$

(18)

whereas when $\epsilon_{\text{ff}} < \epsilon_{\text{ad}}$,

$$T_e = 2 \times 10^6 T^{2/5} \text{K} ;$$

(19)

In equation (19) the physical parameters for the $n = 1$ case in Table 1 are used. If we equate the ion and electron temperatures in equations (18) and (19), we can derive the critical temperature $T_1$ above which the jet plasma is in the two-temperature regime,

$$T_1 = 2 \times 10^6 \frac{2^{3/2}}{T^{2/5}} \text{K} \text{ for } \epsilon_{\text{ff}} > \epsilon_{\text{ad}}$$

(20)
and

\[ T_1 = 6.9 \times 10^8 \text{ K} \quad \text{for ad}: \quad (21) \]

We choose the position of \( r = r_1 \) as the new ductal point and normalize the physical quantities with those at \( r = r_1 \), \( x = r = r_1 \), \( y = T = T_1 \), and \( z = = 1 \). The dimensionless equation (5) with the free parameter \( r_1 \) replaced for \( 0 \) is again derived from the ion energy equation. The parameter \( r_1 \) is now re-defined as the ratio of the flow time to the ion energy loss time or the ion-electron scattering time given by

\[ t_{ie} = \frac{t}{r_1} : \quad (22) \]

Furthermore, the ion energy loss rate is written in the dimensionless form as

\[ f = zy^{2+n} : \quad (23) \]

We solve equation (5) together with equations (4) and (23) and derive the analytic solution,

\[ y^{3+5} = \sqrt{\frac{\frac{8}{x^{n+1}} + \frac{1}{x^{n+1}} + \frac{1}{x^{n+1}}}{\frac{1}{x^{n+1}} + \frac{3}{x^{n+1}}}} \quad \text{for } n = 1 \]

\[ y^{3+5} = \sqrt{\frac{\frac{8}{x^{n+1}} + \frac{1}{x^{n+1}} + \frac{1}{x^{n+1}}}{\frac{1}{x^{n+1}} + \frac{3}{x^{n+1}}}} \quad \text{for } n = 2 : \quad (24) \]

Using equation (16) and integrating the high energy emission along the jet, we obtain the luminosity of high energy photons emitted outside the distance \( x \). The luminosity \( L(x) \) is approximately given by

\[ L(x) = S \int_{r_1}^{1} f(x) h(x) \text{ ergs s}^{-1} : \quad (25) \]

where

\[ h(x) = \sqrt{\frac{\frac{15}{4} + \frac{3}{2} + \frac{3}{2} + \frac{3}{2} + \frac{1}{x^{n+1}}}{\frac{1}{x^{n+1}} + \frac{3}{x^{n+1}}}} \quad \text{for } n = 1 \]

\[ h(x) = \sqrt{\frac{\frac{15}{4} + \frac{3}{2} + \frac{3}{2} + \frac{1}{x^{n+1}}}{\frac{1}{x^{n+1}} + \frac{3}{x^{n+1}}}} \quad \text{for } n = 2 : \quad (26) \]

The outer solutions (11) are connected to the inner solutions (24) at \( r = r_1 \), thereby yielding a break in the temperature distribution. As we proceed inwards along the jet, the ion and electron temperatures increase following equations (18), (19) and (24). Moreover, the ion temperature increases faster than the electron temperature, rendering the jet of two-temperature. As we move further inwards, we reach the sonic point where the ion
sound velocity becomes equal to the \textit{flow} velocity. Although derived by ignoring the pressure gradient force and by assuming the constant \textit{flow} velocity, the above solution may be used down to the sonic point as long as the approximate estimates of the jet parameters are concerned. We list the physical quantities at the sonic point, which are denoted with the subscript $s$, in the Table 3. Here, for simplicity, the Compton enhancement factor is set as 1.

In the conical jet case electrons lose energy mainly by emitting radiations. In Table 3 the radiative cooling is adopted for the $n = 2$ case. The sonic point is located very far from the central engine. The ion temperature is approximately an order of magnitude higher than the electron temperature. The thermal equilibrium is not complete among ions since the ion-ion scattering time exceeds the \textit{flow} time. As seen from the values of $v_1$ and $\lambda$, the radiative cooling as well as the adiabatic cooling contributes significantly to the energy loss of plasma in the two-temperature region of the jet. We find that the luminosity of the high energy photons emitted from the region outside the sonic point amounts to $2 \times 10^8$ erg s$^{-1}$, which is approximately comparable to the kinetic luminosity of the outflowing matter in the jet beam.

In the $n = 1$ case electrons lose energy mainly by adiabatically expanding. In Table 3 the adiabatic cooling is adopted for the $n = 1$ case. The sonic point is located close to the central engine. As in the $n = 2$ case the analytic solution also yields the electron temperature an order of magnitude lower than the ion temperature and large luminosity of high energy photons. Note, however, that at the sonic point the radius of the jet cross section $R_s$ is an order of magnitude larger than the distance $r_s$. Although assumed in the calculation, the uniformity of physical parameters over the jet cross section may not be guaranteed when $R < r$. Hence, the physical parameters at the sonic point, shown in Table 3, may not be reliable. We expect that the analytic solution for the $n = 1$ case can be applicable down to the point where $R = r$. We list the physical quantities there in the Table 4. The two-temperature solution for the $n = 1$ case can extend down to the distance $r = 2.3 \times 10^8$ cm and cannot reach the sonic point keeping $R < r$.

Let us consider the hybrid jet model combining the $n = 1$ and $n = 2$ cases. We adopt the $n = 1$ case presented above to describe the outer part of the jet beyond the distance $r = 2.3 \times 10^8$ cm, while for the inner part we adopt the $n = 2$ case (conical jet). The conical jet extends inwards starting from the boundary with the physical quantities shown in Table 4. We approximate the electron cooling rate by the radiative loss rate. The density and ion and electron temperatures increase with decreasing distance, following equations (4), (24) and (18). We reach the sonic
point at the distance $r_s = 9.2 \times 10^7$ cm and derive physical quantities such as shown in Table 5. Note that the sonic point in the hybrid case locates much closer to the central engine compared to the simple conical case shown in Table 3. The luminosity of high energy photons emitted from the region outside the sonic point is also very large and amounts to an important fraction of the kinetic luminosity of the outgoing matter. The other properties of the two-temperature jet are more or less similar to those of the simple conical case.

Fukue (1987) already considered the hybrid model for the SS 433 jets. Contrary to our hybrid model, he adopted the $n = 1$ and $n = 2$ beams respectively for the inner and outer parts of jets. The sonic points lie close to the compact objects similarly to our calculation for the $n = 1$ case (Table 3). The boundary between the $n = 1$ and $n = 2$ beams may roughly correspond to the base of the X-ray emitting region. If we adopt a standard set of parameters for the physical quantities at the base (Kotani et al. 1996), we obtain the radius of the jet cross section at the sonic point, which exceeds the distance of the sonic point from the compact stars, especially in the neutron star case. The uniformity of the physical parameters mentioned above may not be guaranteed also in the hybrid model by Fukue (1987).

We note that the electron-positron pairs and appropriate Compton amplification in addition to the pressure gradient force should be included in the calculation in order to have more accurate estimates on the jet property especially around the sonic point. Even if included, the qualitative properties may not deviate significantly from those obtained here.

5. Discussion and Conclusions

The jet beams in SS 433 may originate near the compact object, or more specifically in the inner region of the accretion disk. The X-ray emitting region of the jet is likely to be located at the distance of $> 10^{11} - 10^{12}$ cm from the compact object. The jet beams must be accelerated and collimated to reach the terminal velocity within the distance of $< 10^{11} - 10^{12}$ cm. The mechanism of acceleration and collimation for the jet beams in SS 433 are poorly understood. In general, the gas and radiation pressures and magnetic field are considered as a possible driving force for the jet acceleration.

If the shape of the SS 433 jets is simply conical in the X-ray emitting region and also in the inner region adjacent to it, we find that the sonic point should be located very far from the central and compact object. The ion temperature at the sonic point is very high and close to the maximum attained near the compact object. It is quite difficult to
keep the jet matter so hot when the matter out flows from the jet footpoint near the central object to the distant sonic point. The jet matter will suffer from the adiabatic cooling and lower the temperature substantially unless the shape of the jet is completely columnar in the region from the footpoint to the sonic point. Let us turn to the jet acceleration in this conical case. The free fall velocity at the sonic point due to the gravity of the compact object is more than an order of magnitude smaller than the jet velocity. Hence, the acceleration due to the gas pressure may not be applicable in this case. The radiative acceleration is also ruled out since the inner and hotter portion of the jets is optically thick along the flow direction and hence photons from outside cannot enter into the jet and impart momentum to the matter. The magnetic driving still remains as a possible acceleration mechanism. These arguments indicate that the simple conical model for the SS 433 jets is less likely.

Promising is the hybrid model presented in the previous section. We adopt the model jet with \( n = 1 \), where the cross section of the jet grows with the distance more slowly than that of the conical jet, in order to describe the outer part of the jet including the X-ray emitting region. We use the conical jet to describe the inner and hotter part of the jet. This model explains the properties of observed X-rays well. Furthermore, in the hybrid model the sonic point can come close to the central object. Hence, the gas pressure as well as the magnetic force may also be considered as a possible driving force for the jet acceleration. The radiative acceleration is again ruled out since the inner and hotter portion of the jets is optically thick along the flow direction. We note that the inner and hotter portion of the jets emit a huge amount of gamma rays. No observational evidence, however, has not been found for an emission of such high energy photons. Hence, we conclude that the inner and hotter portions of the jets are hidden by the surrounding matter, most probably by the thick envelope and accretion disk. Note that such an envelope, or a dense outflowing atmosphere which envelops the system, is also suggested from the substantial fluctuations of the optical magnitudes and the infrared spectrum (Vermue 1989; B and 1987).

The collimation of the jet beams is another important issue in the study of the astrophysical jet. The hybrid model above indicates that the jet beam may be squeezed and collimated more strongly around the distance of \( 10^9 \) cm. We expect that at squeezing a part of the kinetic energy of the jet matter may be dissipated into heat and reheat the jet matter. A substantial amount of surrounding matter is also required, again, if it is responsible for squeezing, from the pressure balance with the ram pressure of the jet matter. If the thick accretion disk channels the jet beam and precesses, the precession of the jet would be a natural consequence. The magnetic component is another possibility for collimation. Our studies show that the magnetic fields, which yield the magnetic pressure...
comparable to the gas pressure at the sonic point, are of the order of $10^7$ G. This field strength may also be used to study and set constraints on the properties of the magnetically driven jets.

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Table 1. Physical quantities at the base of the X-ray emitting region.

| \( n \) | \( r_0 \) | \( R_0 \) | \( T_0 \) | \( M_0 \) | \( L(\alpha_0) \) | \( L_k \) |
|-------|--------|--------|--------|--------|-------------|--------|
|       | \( \times 10^6 \text{ cm} \) | \( \times 10^5 \text{ cm} \) | \( \times 10^{11} \text{ g cm}^{-3} \) | \( \times 10^8 \text{ K} \) | \( \times 10^5 \text{ M yr}^{-1} \) | \( \times 10^{35} \text{ ergs s}^{-1} \) |
| 1     | 6.42   | 12     | 4.1    | 2.3    | 0.05       | 2.3    | 1.9    | 4.4    |
| 2     | 5.2    | 2.3    | 1.5    | 2.3    | 0.15       | 3.1    | 0.97   | 5.9    |

Table 2. Physical quantities at the boundary inside of which the jet plasma is in the two-temperature regime.

| \( n \) | \( r_1 \) | \( R_1 \) | \( T_1 \) | \( L(\alpha_1) \) |
|-------|--------|--------|--------|-------------|
|       | \( \times 10^6 \text{ cm} \) | \( \times 10^5 \text{ cm} \) | \( \times 10^{10} \text{ cm}^{-3} \) | \( \times 10^8 \text{ K} \) | \( \times 10^{36} \text{ ergs s}^{-1} \) |
| 1     | 1.3    | 5.5    | 2.0    | 6.9        | 0.67       | 1.9    |
| 2     | 12     | 5.5    | 2.6    | 20         | 1.6        | 12     |

Table 3. Physical quantities at the sonic point.

| \( n \) | \( r_s \) | \( R_s \) | \( T_s \) | \( T_{as} \) | \( L(\alpha_s) \) |
|-------|--------|--------|--------|--------|-------------|
|       | \( \times 10^6 \text{ cm} \) | \( \times 10^8 \text{ cm} \) | \( \times 10^8 \text{ cm}^{-3} \) | \( \times 10^9 \text{ K} \) | \( \times 10^9 \text{ K} \) | \( \times 10^{35} \text{ ergs s}^{-1} \) |
| 1     | 4.3    | 1.0    | 6.1    | 4.4    | 9.1         | 0.014   | 0.084  |
| 2     | 1.1    | 1.0    | 5.2    | 2.9    | 2.9         | 0.4     | 0.64   | 3.8    |

Table 4. Physical quantities at the distance where \( R = r \) in the \( n = 1 \) case.

| \( r \) | \( R \) | \( T \) | \( T_{as} \) | \( L(\alpha) \) |
|-------|--------|--------|--------|-------------|
|       | \( \times 10^7 \text{ cm} \) | \( \times 10^9 \text{ cm} \) | \( \times 10^9 \text{ cm}^{-3} \) | \( \times 10^9 \text{ K} \) | \( \times 10^9 \text{ K} \) | \( \times 10^{37} \text{ ergs s}^{-1} \) |
| 2.3   | 2.3    | 1.1    | 4.2    | 1.4        | 0.23       | 1.6    |
Table 5. Physical quantities at the sonic point in the hybrid model.

| $r_s$ | $R_s$ | $n$ | $T_s$ | $T_{ws}$ | $L(\kappa_s)$ |
|-------|-------|-----|-------|---------|----------------|
| $\left(10^7 \text{ cm}\right)$ | $\left(10^7 \text{ cm}\right)$ | $\left(10^7 \text{ g cm}^{-3}\right)$ | $\left(10^{11} \text{ K}\right)$ | $\left(10^{15} \text{ K}\right)$ | $\left(10^{39} \text{ ergs s}^{-1}\right)$ |
| 9.2  | 9.2   | 6.9 | 4.4   | 1.7     | 0.13           | 1.3            |