EFFECTS OF MAGNETIC FIELD AND FAR-ULTRAVIOLET RADIATION ON THE STRUCTURES OF BRIGHT-RIMMED CLOUDS

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ABSTRACT

The bright-rimmed cloud SFO 22 was observed with the 45 m telescope of Nobeyama Radio Observatory in the
\(^{12}\text{CO} (J = 1–0)\), \(^{13}\text{CO} (J = 1–0)\), and \(^{18}\text{O} (J = 1–0)\) lines, where well-developed head–tail structure and small
line widths were found. Such features were predicted by radiation-driven implosion models, suggesting that SFO
22 may be in a quasi-stationary equilibrium state. We compare the observed properties with those from numerical
models of a photoevaporating cloud, which include effects of magnetic pressure and heating due to strong far-
ultraviolet (FUV) radiation from an exciting star. The magnetic pressure may play a more important role in the
density structures of bright-rimmed clouds than the thermal pressure that is enhanced by the FUV radiation. The
FUV radiation can heat the cloud surface to near 30 K; however, its effect is not enough to reproduce the observed
density structure of SFO 22. An initial magnetic field of 5 \(\mu\)G in our numerical models produces the best agreement
with the observations, and its direction can affect the structures of bright-rimmed clouds.

Key words: ISM: clouds – ISM: individual objects (SFO22) – ISM: magnetic fields – methods: numerical –
methods: observational

Online-only material: color figures

1. INTRODUCTION

Bright-rimmed clouds (BRCs) are cometary molecular clouds found at the edge of H\(\text{II}\) regions. These clouds have bright rims
on the side facing the exciting star and extended tails on the other
side. Since their head–tail morphologies suggest that BRCs are
interacting with the radiation or stellar wind from an exciting
star, BRCs are considered to be potential sites of triggered star
formation. The gradients of age spread in young stars along
the axes of BRCs indicate that their formation may have been
sequentially triggered by shock waves (Sugitani et al. 1995;
Getman et al. 2007; Ikeda et al. 2008; Getman et al. 2009).

Radiation-driven implosion models are often considered for
the formation and evolution of BRCs and their triggered origins.
Strong UV radiation from nearby massive stars can photoionize
and photoevaporate the surfaces of surrounding molecular
clouds, and whose effects have been studied by various groups.
Bertoldi (1989) developed an approximate analytical solution
for the evolution of molecular cloud compressed by radiation-
driven implosion. Lefloch & Lazareff (1994) investigated a
radiation-driven implosion model using hydrodynamic simul-
ations. Recent hydrodynamic simulations of radiation-driven
implosion include effects of physics such as self-gravity of the
gas (Kessel-Deynet & Burkert 2003; Miao et al. 2006), diffuse
radiation field (Haworth & Harries 2012), and turbulence in
molecular clouds (Gritschneder et al. 2009). Motoyama et al.
(2007) demonstrated that radiation-driven implosion can en-
hance accretion rates enough to account for the high luminosi-
ties of young stellar objects observed in the BRCs (Sugitani
et al. 1989). Typical shock speed of a few \(\text{km}\,\text{s}^{-1}\) in this
study is consistent with that estimated from observations of age

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implosion has an initial implosion phase followed by a quasi-stationary equilibrium phase. In this paper, we focus on the quasi-stationary equilibrium phase, and implosion phase will be investigated in a subsequent paper. The BRC SFO 22 was observed with the 45 m telescope of Nobeyama Radio Observatory, and the results were compared with numerical models of photoionized clouds with the effects of magnetic field and FUV radiation. The layout of this paper is as follows. In Section 2, the details of observations are described. In Section 3, a description of our numerical models is given. Sections 4 and 5 give the results and discussions. In Section 6, we summarize our main conclusions.

2. OBSERVATIONS AND ANALYSIS

2.1. Observed Bright-rimmed Cloud

BRC SFO 22 is located at the eastern edge of H\(\text{\textsc{ii}}\) region s281, and was selected from BRC catalog of Sugitani et al. (1991). Figure 1(a) shows the entire image of the region s281, and Figure 1(b) gives the close-up view of SFO 22 enlarged from Figure 1(a). This H\(\text{\textsc{ii}}\) region is ionized by \(\theta^1\) Ori, marked by a cross in Figure 1(a). The spectral type of the primary exciting star in \(\theta^1\) Ori is O7V, and has a projected distance of 6.5 pc to SFO 22 (Morgan et al. 2004). S281 (Blaauw 1964) is 460 pc away from us.

Sugitani et al. (1991) classified the BRCs into three types in order of increasing degree of rim curvature: types A, B, and C. Based on the radiation-driven implosion model, the shapes of cloud rims reflect the evolutionary stages. The type A BRCs are still undergoing compression by the shock waves generated by ionization, and the type B and type C BRCs are approaching or have already reached the phase of quasi-stationary equilibria. SFO 22 has a well-developed head–tail structure along the line to the exciting star and it is classified as type B. Although the head part of the cloud contains the IRAS point source 05359-0515, ammonia rotational inversion lines were not detected toward this IRAS point source (Morgan et al. 2010). Since ammonia lines trace dense gas associated with protostellar cores, the non-detection of ammonia lines has been interpreted as no star forming activities in SFO 22.

2.2. Observations

Observations were carried out using the 45 m telescope of Nobeyama Radio Observatory in 2005 January and April. We observed \(^{12}\)CO \((J = 1–0)\) at 115.271203 GHz, \(^{13}\)CO \((J = 1–0)\) at 110.201370 GHz, and \(^{18}\)O \((J = 1–0)\) at 109.782182 GHz. The half-power beam width of the telescope and main-beam efficiency at 115 GHz were 15\(\mathrm{\arcsec}\) and \(n_{\text{MB}} = 0.4\), respectively. We used the 5 \(\times\) 5 beam focal plane array receiver “BEARS” whose beam separation is 41\(\mathrm{\arcsec}\). As receiver backends we used a 1024 channel digital autocorrelator with a 31.25 kHz frequency resolution. The corresponding velocity resolution is 81.5 m s\(^{-1}\) at 115 GHz. The typical system noise temperature was 300–450 K depending on the atmospheric conditions. The intensity scale of the spectra was calibrated by the chopper wheel method. The corrected antenna temperature \(T_A^*\) is converted into main beam brightness temperature using the relation of \(T_B = T_A^*/n_{\text{MB}}\).

We observed SFO 22 with a grid spacing of 20\(\mathrm{\arcsec}\)55, which is half of the beam separation of BEARS, in the line of \(^{12}\)CO \((J = 1–0)\). The mapped area was 390\(\mathrm{\arcsec}\) \(\times\) 390\(\mathrm{\arcsec}\). Dense regions of clouds were observed with finer grid spacing of 10\(\mathrm{\arcsec}\)3 in the lines of \(^{13}\)CO \((J = 1–0)\) and \(^{18}\)O \((J = 1–0)\). The mapped area for these lines were 195\(\mathrm{\arcsec}\) \(\times\) 195\(\mathrm{\arcsec}\) and 154\(\mathrm{\arcsec}\) \(\times\) 154\(\mathrm{\arcsec}\), respectively. The pointing accuracy of the antenna was checked and corrected every 1.5–2 hr using SiO maser emission from Ori KL, and its typical error was less than 5\(\mathrm{\arcsec}\). All observations were carried out by position switching mode. The data were reduced by using the software package NewStar provided by Nobeyama Radio Observatory.

2.3. Observational Results and Analysis

Figure 2 shows the velocity-integrated intensity maps of SFO 22. The reference center of the map is the peak position of \(^{18}\)O \((J = 1–0)\) emission at R.A. (2000) = 5\(^{h}\)38\(^{m}\)21\(^{s}\)6, decl. (2000) = −5\(^{\circ}\)13\(\arcmin\)37\(\arcsec\)8. Emission from \(^{12}\)CO \((J = 1–0)\)
coincides with the optical images. The cometary morphology is clearly shown. On the contrary, the C\textsuperscript{18}O (J = 1–0) emission is very weak and detected only at a few points.

Figure 3 shows the observed line spectra toward the peak position of C\textsuperscript{18}O (J = 1–0) and offset positions along declination. Assuming that 12CO (J = 1–0) emission is optically thick at the peak of C\textsuperscript{18}O (J = 1–0) emission, we can calculate the excitation temperature as

\[ T_{\text{ex}} = \frac{5.53}{\ln[1 + 5.53/(T_B(12\text{CO}) + 0.819)]}, \]

where \( T_B(12\text{CO}) \) is the brightness temperature of 12CO (J = 1–0) at the peak of C\textsuperscript{18}O (J = 1–0). The excitation temperature of SFO 22 is found to be 27.1 ± 1.8 K. Figure 4 shows the position–velocity diagrams of 12CO (J = 1–0) (left), C\textsuperscript{18}O (J = 1–0) (center), and C\textsuperscript{13}O (J = 1–0) (right) along declination through the peak position of C\textsuperscript{18}O (J = 1–0) emission. The diagram for 12CO (J = 1–0) has lowest contour of 1.53 K and contour interval of 1.53 K (3σ). The diagram for C\textsuperscript{13}O (J = 1–0) has lowest contour of 0.276 K (3σ) and contour interval of 0.125 K (3σ). The C\textsuperscript{18}O (J = 1–0) map (bottom) has a lowest contour of 0.125 K (3σ) and contour interval of 0.0435 K (1σ).

Figure 2. Integrated intensity maps of SFO 22. The 12CO (J = 1–0) map (top) has a lowest contour of 1.39 K km s\(^{-1}\) (3σ) and contour intervals of 1.39 K km s\(^{-1}\) (3σ). The C\textsuperscript{18}O (J = 1–0) map (middle) has a lowest contour of 0.315 K km s\(^{-1}\) (3σ) and contour intervals of 0.525 K km s\(^{-1}\) (5σ). The C\textsuperscript{13}O (J = 1–0) map (bottom) has a lowest contour of 0.131 K km s\(^{-1}\) (3σ) and contour intervals of 0.0435 K km s\(^{-1}\) (1σ).

Figure 3. Some selected 12CO (J = 1–0), 13CO (J = 1–0), and C\textsuperscript{18}O (J = 1–0) spectra observed toward the SFO 22 along declination through the peak of C\textsuperscript{18}O (J = 1–0).

Figure 4. Position–velocity diagrams of 12CO (J = 1–0) (left), 13CO (J = 1–0) (center), and C\textsuperscript{18}O (J = 1–0) (right) along declination through the peak positions of C\textsuperscript{18}O (J = 1–0) emission. The diagram for 12CO (J = 1–0) has lowest contour of 1.53 K (3σ) and contour interval of 1.53 K (3σ). The diagram for C\textsuperscript{18}O (J = 1–0) has lowest contour of 0.276 K (3σ) and contour interval of 0.125 K (3σ). The vertical dotted lines indicate the systemic velocity of 10.4 km s\(^{-1}\).
same as the $^{12}$CO line, we can calculate the optical depth of $^{13}$CO and C$^{18}$O using
\[
\tau_{13} = -\ln \left( 1 - \frac{T_B(^{13}\text{CO})}{5.29(1/(\exp(5.29/T_{ex}) - 1)) - 0.164} \right),
\]
and
\[
\tau_{18} = -\ln \left( 1 - \frac{T_B(\text{C}^{18}\text{O})}{5.27(1/(\exp(5.27/T_{ex}) - 1)) - 0.166} \right),
\]
respectively. The column densities of $^{13}$CO and C$^{18}$O molecules can be derived as
\[
N(^{13}\text{CO}) = 2.42 \times 10^{14} \frac{\tau_{13}\Delta v_{13}T_{ex}}{1 - \exp[-5.29/T_{ex}]},
\]
and
\[
N(\text{C}^{18}\text{O}) = 2.42 \times 10^{14} \frac{\tau_{18}\Delta v_{18}T_{ex}}{1 - \exp[-5.27/T_{ex}]},
\]
where $\Delta v_{13}$ and $\Delta v_{18}$ are the line widths of the $^{13}$CO ($J = 1\rightarrow0$) and C$^{18}$O ($J = 1\rightarrow0$) emission, respectively. The column density of $^{13}$CO is converted to the column density of H$_2$ by assuming an abundance ratio of $N(\text{H}_2)/N(^{13}\text{CO}) = 5.0 \times 10^5$ (Dickman 1978). Under the environment where molecular clouds are illuminated by strong UV radiation, abundance ratio of $N(\text{H}_2)/N(\text{C}^{18}\text{O})$ are thought to be affected by selective destruction by UV radiation (Glassgold et al. 1985). We follow Niwa et al. (2009) to obtain the column density of H$_2$ from the column density of C$^{18}$O. The column densities of $^{13}$CO and C$^{18}$O can be formulated by least-squares fitting as
\[
N(\text{C}^{18}\text{O}) = 3.91 \times 10^{-2} \times N(^{13}\text{CO}).
\]
An abundance ratio of $N(\text{H}_2)/N(\text{C}^{18}\text{O}) = 1.28 \times 10^7$ can be derived. This value is slightly larger than the standard value of $6.0 \times 10^6$ for molecular clouds not associated with H II regions (Fereking et al. 1982). Figure 5 shows that the column density profiles obtained here are nearly flat with the column density of $\sim10^{22}$ cm$^{-2}$. Adopting a distance of 460 pc to SFO 22, the total masses traced by $^{13}$CO emission and C$^{18}$O emission are $M_{13} = 12.0 M_\odot$ and $M_{18} = 5.3 M_\odot$, respectively.

### 3. MODEL DESCRIPTION

Our numerical model is based on the analytic model of Bertoldi & McKee (1990) for a photoevaporating cloud in the quasi-stationary equilibrium state with a polytropic equation of state. The polytropic gas is a good approximation for the cases where either gas pressure or magnetic pressure is dominant. In an actual bright-rimed cloud, these two quantities may have been comparable before the compression by radiation-driven implosion alter the state, and FUV radiation will affect the thermal structure through photoelectric heating and photodissociation of molecular coolants. Here we adopt a more realistic model with the inclusion of thermal pressure and magnetic pressure explicitly and the heating due to FUV radiation.

#### 3.1. Density Structure

Total pressure of the gas is expressed as
\[
P_{\text{tot}} = P_{\text{th}} + P_{\text{mag}} = \frac{c_s^2 \rho}{\gamma} + \frac{B^2}{8\pi},
\]
where $P_{\text{th}}$, $P_{\text{mag}}$, $c_s$, $\rho$, $\gamma$, and $B$ are the thermal pressure, the magnetic pressure, the sound speed, the density of the cloud, the ratio of specific heats, and the magnetic field strength, respectively. A $\gamma = 5/3$ is adopted, which is appropriate for the molecular clouds because the molecular hydrogen behaves like a monoatomic gas at temperature $\lesssim 100$ K. We assume an ideal gas, so that the sound speed $c_s$ is related to the gas temperature $T$ as
\[
c_s = \sqrt{\frac{\gamma k_B T}{\mu m_\text{H}}},
\]
where $k_B$ and $\mu$ are the Boltzmann constant and mean mass per nucleus in units of the hydrogen mass $m_\text{H} = 1.67 \times 10^{-24}$ g and $\mu = 1.15$, respectively. For simplicity, the effects of the magnetic field are approximated through
\[
B = B_0 \left( \frac{\rho}{\rho_0} \right)^{a},
\]
where $B_0$ and $\rho_0$ are magnetic field strength and density of the cloud before undergoing compression by radiation-driven implosion. The exponent $a$, which ranges from 0 to 1, is a parameter representing how much the magnetic field is trapped in the gas during the compression. Figure 6 shows schematic drawings of two extreme cases by assuming that compression of a cloud perpendicular to the direction of radiation is small. If the cloud is compressed along the magnetic field, the strength of the field increases as $B \propto \rho$ during compression, i.e., $a \approx 0$. On the other hand, if the cloud is compressed perpendicular to the magnetic field, the strength of the field increases as $B \propto \rho$ during compression, i.e., $a \approx 1$. The value of $a$ depends on the initial configuration of the magnetic field and the shape of cloud. We leave $a$ as an open parameter as it is hard to determine an accurate value without launching MHD simulations. We also neglect the diffusion of the magnetic field due to the longer timescale of ambipolar diffusion compared to the dynamical timescale of the radiation-driven implosion.

We calculate the structure of the cloud in axisymmetry along the line to the exciting star. We also assumed that the distance from the cloud to the exciting star is larger than size of the...
The ionized gas evaporates off the cloud surface with angle $\theta$. (Left) The magnetic field is parallel to the direction of the UV radiation. (Right) The magnetic field is perpendicular to the direction of the UV radiation.

Figure 7 illustrates the coordinates system we use in this paper. UV radiation propagates downward, and the cloud is compressed only along this direction in both cases. Bertoldi & McKee (1990) showed that the position of the cloud surface can be approximated as $z_{\text{surf}} = R_c a^{-2} \ln \cos(ar/R_c)$, where $R_c$ and $a$ are the curvature radius at $z = 0$ and the cloud width parameter defined in Bertoldi & McKee (1990), respectively. The method used to determine $a$ and $R_c$ is described in Section 3.3.

In this study, we assume that all parts of the cloud are subject to the same acceleration through the rocket effect of the photoevaporation flow, as the cloud is in a quasi-stationary equilibrium state. The equation of hydrostatic equilibrium for the cloud is

$$\frac{dP_{\text{tot}}}{dz} = g \rho,$$

where $g$ is the acceleration of the cloud. With Equations (7) and (9), this equation can be rewritten as

$$\frac{d \rho}{dz} = \frac{g \rho - 2 c_s \rho / \gamma (d c_s / dz)}{c_s^2 / \gamma + 2 \alpha B_0 \rho (\rho / \rho_0)^{2 \alpha - 1} / 8 \pi \rho_0}.$$

The density distribution inside the cloud is determined by solving this equation with the appropriate boundary conditions. The boundary conditions at cloud surface are determined using jump conditions for D-critical ionization front. Therefore, the pressure at the cloud surface is given by

$$P_{\text{surf}}(r) = 2 \mu m_H c_i F_{\text{UV}}(r) \cos \theta,$$

where $c_i = 10 \text{ km s}^{-1}$ and $F_{\text{UV}}(r)$ are the sound speed of the ionized gas and the ionization photon flux reaching the ionization front, respectively, and the width of the ionization front is negligible. Since some part of the incident ionizing UV photons is consumed by recombined hydrogen in the photoevaporation flow, the ionizing UV photon flux arriving at the cloud surface is written as

$$F_{\text{UV}}(r) = F_i - \int_{z_{\text{surf}}}^{\infty} \alpha B n_e(r, z) n_p(r, z) dz,$$

where $F_i, \alpha_B = 2.7 \times 10^{-13} \text{ cm}^3 \text{s}^{-1}$, $n_e$, and $n_p$ are the incident ionizing photon flux, the hydrogen electronic recombination coefficient into the excited state, the electron number density, and the proton number density, respectively. Following Bertoldi & McKee (1990), we introduce a dimensionless parameter $\omega$ that represents the effective fractional thickness of the recombination layer. Equation (14) can be rewritten as

$$F_{\text{UV}}(r) = F_i - \omega(r) \alpha_B n_{\text{HII}}(r = 0) R_c,$$

where $n_{\text{HII}}$ is the hydrogen number density just behind the ionization front. If we assume that the ionized gas streams away from the ionization front with the velocity of the speed of sound, and the stream line is normal to the cloud surface, we can derive the form

$$\omega(r) \simeq 3 \omega(0) \int_0^r \left[ \frac{r' P_{\text{tot}}(r')}{r P_{\text{tot}}(0)} \right]^2 \frac{R(r')}{[R(r') \sin \theta' + r - r'] \cos \theta' R_c} \frac{dr'}{r},$$

where $R(r')$ is the curvature radius of the cloud surface at $r = r'$. We adopt $\omega$ for a spherical cloud with radius $R_c$ at the cloud tip:

$$\omega(0) = \frac{q(q - 1)}{\psi},$$

where $q$ and $\psi$ are the ratio of incident ionizing photon flux $F_i$ to ionizing photon flux reaching the ionization front.
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\[ F_{\text{UV}} \] and the photoevaporation parameter, respectively. The photoevaporation parameter is defined as

\[ \psi = \frac{\alpha \gamma F_{\text{UV}} R_e}{c_s^2}. \]  

(18)

The value of \( \psi \) in our numerical models ranges from 74 to 104 depending on the model parameters. Spitzer (1978) derived an analytic estimation of \( q \) as

\[ q = \frac{1 + (1 + 1.5 \psi^{1/4})^2}{8}. \]  

(19)

The density and pressure distributions of the cloud are characterized by scale height defined as \( h_c = \rho_{\text{tot}}(z = 0) / g \rho(z = 0) \). If \( \psi \gg 1 \), which is the case for SFO 22, \( h_c \) is related to \( R_e \) as \( R_e = 0.5h_c \).

### 3.2. Thermal and Chemical Model

We solve the reaction networks for the species of \( \text{H}_2, \text{CO}, \text{C}^+, \) and the electron \( e \). We adopt the simplified reaction model as described in Nelson & Langer (1997) to determine the abundance of \( \text{CO} \) molecules. In this reaction model, \( \text{C}^+ \) is directly converted to \( \text{CO} \) without accounting explicitly for the intermediate reactions. The formation rate of \( \text{CO} \) molecules is expressed as

\[ R_{\text{CO}} = 5 \times 10^{-16} n(\text{C}^+) n(\text{H}_2) \beta, \]  

(20)

where \( n(\text{C}^+) \) and \( n(\text{H}_2) \) are the number densities of \( \text{C}^+ \) and \( \text{H}_2 \), respectively. The coefficient \( \beta \) is defined as

\[ \beta = \frac{5 \times 10^{-10} X(\text{O})}{5 \times 10^{-10} X(\text{O}) + D_{\text{CH}_4}/n(\text{H}_2)}, \]  

(21)

where \( X(\text{O}) \) and \( D_{\text{CH}_4} \) are the fractional abundance of oxygen and the total photodissociation rate of both \( \text{CH} \) and \( \text{CH}_2 \). This total photodissociation rate is written as

\[ D_{\text{CH}_4} = 5 \times 10^{-10} G_0 \exp(-\tau_{\text{UV}}), \]  

(22)

where \( G_0 \) and \( \tau_{\text{UV}} \) are the intensity of the incident FUV radiation in terms of the Habing interstellar radiation field (Habing 1968) and the optical depth in UV range, respectively. The optical depth \( \tau_{\text{UV}} \) is related to the visual extinction \( A_v \) by \( \tau_{\text{UV}} = 2.5A_v \). We adopt the conversion factor between the visual extinction and the total hydrogen column density as \( X_{A_v} = A_v / N_H = 6.3 \times 10^{-22} \text{mag cm}^2 \) in this paper. The photodissociation rate of \( \text{CO} \) by the FUV radiation is written as

\[ D_{\text{CO}} = 10^{-10} G_0 \exp(-\tau_{\text{UV}}) n(\text{CO}), \]  

(23)

where \( n(\text{CO}) \) is the number density of \( \text{CO} \). The abundance of \( \text{CO} \) is calculated by solving the equation of formation and dissociation balance

\[ R_{\text{CO}} - D_{\text{CO}} = 0. \]  

(24)

Abundances of other species are calculated as follows. The cloud is assumed to be composed of molecular hydrogen, so that the number density of \( \text{H}_2 \) is written as

\[ n(\text{H}_2) = 0.5n, \]  

(25)

where \( n \) is the number density of hydrogen nuclei and related to the mass density as

\[ n = \frac{\rho}{\mu m_H}. \]  

(26)

We assume that carbon exists in ionized form in the cloud as carbon is easily photoionized by FUV radiation owing to its lower ionization energy (11.2 eV) compared to that of hydrogen. Although this assumption may cause an overestimation of the cooling rate through \( \text{C}^+ \) in the deep inner region of the cloud where FUV is strongly attenuated and rotational line emission from \( \text{CO} \) is a more important cooling process. Our assumption does not affect the numerical results, however. The number density of \( \text{C}^+ \) is calculated by

\[ n(\text{C}^+) = X(\text{C}_{\text{tot}}) n - n(\text{CO}), \]  

(27)

where the elemental abundance of carbon is taken to be \( X(\text{C}_{\text{tot}}) = 10^{-4} \). We assume that oxygen exists in atomic form in the cloud, because its ionization energy (13.6 eV) is similar to that of hydrogen. The number density of oxygen is calculated by

\[ n(\text{O}) = X(\text{O}_{\text{tot}}) n - n(\text{CO}), \]  

(28)

where the elemental abundance of oxygen is taken to be \( X(\text{O}_{\text{tot}}) = 2.0 \times 10^{-4} \). Constant electron fraction \( n_e / n = 10^{-7} \) is also assumed to calculate the number density of the electron.

For the heating processes in the cloud, we consider photoelectric heating and cosmic ray heating. The photoelectric heating rate is (Bakes & Tielens 1994)

\[ \Gamma_{\text{pe}} = 10^{-24} \epsilon G_0 \exp(-\tau_{\text{UV}}) n \text{ erg cm}^{-3} \text{ s}^{-1}, \]  

(29)

where \( \epsilon \) is the photoelectric heating efficiency

\[ \epsilon = \frac{4.87 \times 10^{-2}}{1 + 4 \times 10^{-3} (G_0 \exp(-\tau_{\text{UV}}) T^{1/2}/n_e)^{0.73}} \]  

\[ + \frac{3.65 \times 10^{-2} (T/10^4)^{0.7}}{1 + 2 \times 10^{-4} (G_0 \exp(-\tau_{\text{UV}}) T^{1/2}/n_e)^{0.7}}. \]  

(30)

Cosmic ray heating becomes the dominant heating process in the inner region where FUV radiation does not penetrate. Cosmic ray heating rate is given by

\[ \Gamma_{\text{cr}} = \zeta_p (\text{H}_2) \Delta Q_{\text{cr}} n(\text{H}_2) \text{ erg cm}^{-3} \text{ s}^{-1}, \]  

(31)

where \( \zeta_p (\text{H}_2) \) is the primary cosmic ray ionization rate of \( \text{H}_2 \) and \( \Delta Q_{\text{cr}} \) is the energy deposited as heat as a result of this ionization. We adopt values of \( \zeta_p (\text{H}_2) = 7.0 \times 10^{-17} \text{ s}^{-1} \) (van Dishoeck & Black 1986) and \( \Delta Q_{\text{cr}} = 20 \text{ eV} \) (Goldsmith & Langer 1978).

For the cooling processes in the cloud, we consider radiation from the CO rotational transitions, collisionally excited line emission from \( \text{C}^+ \) and \( \text{O} \), and collisional heat transfer between gas and dust. The cooling rate due to \( \text{CO} \), \( \Lambda_{\text{CO}} \), is taken from the tabulated cooling function computed by Neufeld et al. (1995) for \( T \leq 100 \text{ K} \) and Neufeld & Kaufman (1993) for \( T > 100 \text{ K} \). The cooling rates due to the collisional excitation of \( \text{C}^+ \) and \( \text{O} \) are taken from Nelson & Langer (1997). The cooling rate due to \( \text{C}^+ \) is

\[ \Lambda_{\text{C}^+} = [1.1 \times 10^{-23} n(\text{C}^+) \exp(-92/T)]/ [1 + (n(\text{H}_2)/n_{\text{crit}})[1 + 2 \exp(-92/T)]], \]  

(32)

where the critical number density is taken to be \( n_{\text{crit}} = 3 \times 10^3 \text{ cm}^{-3} \). The cooling rate due to \( \text{O} \) is

\[ \Lambda_{\text{O}} = 5.0 \times 10^{-27} n(\text{O}) [24 \exp(-228/T)] + 7 \exp(-326/T)]T^{1/2}. \]  

(33)
The cooling rate due to the dust grain is (Hollenbach & McKee 1989)

$$\Lambda_{\text{dust}} = [1.2 \times 10^{-3}] n^2 \left( \frac{T}{1000 \text{K}} \right)^{1/2} \left( \frac{100 \text{Å}}{a_{\text{min}}} \right)^{1/2} \times [1 - 0.8 \exp(-75/T)](T - T_{\text{dust}}),$$

where $a_{\text{min}}$ and $T_{\text{dust}}$ are the minimum radius of grains and the dust temperature, respectively. We used $a_{\text{min}} = 100 \text{Å}$ to calculate the cooling rate by dust grains. The dust temperature is calculated following the method by Hollenbach et al. (1991).

3.3. An Iterative Procedure for Obtaining Numerical Solution

An iterative procedure is used to achieve the density distribution of the cloud. We use a uniform grid of 200 (radial) $\times$ 1000 (axial) cells. The grid spacing is 6.5 $\times$ 10$^{-4}$ pc. For presentation, we symmetrize the results obtained on a grid of 400 $\times$ 1000 cells. In order to fit the width of the cloud with that of SFO 22, the cloud width parameter $a$ is calculated by substituting $r = 0.13$ pc and $z = -0.6$ pc into Equation (10). The procedure is as follows. (1) Equation (12) is numerically solved by the Runge–Kutta method using current temperature and sound speed. (2) The optical depth to the cloud surface is calculated. (3) The chemical reaction network is solved to determine the abundances of included species. (4) The temperature and sound speed are updated using new chemical abundances. The thermal equilibrium is assumed to determine the temperature of the cloud:

$$\Gamma_{\text{cr}} + \Gamma_{\text{pe}} - \Lambda_{\text{CO}} - \Lambda_{\text{C^+}} - \Lambda_{\text{O}} - \Lambda_{\text{dust}} = 0.$$

These processes are repeated until the converged solution is achieved. We have confirmed that relative errors between the two consecutive steps are smaller than 10$^{-2}$ for all models in this paper.

Once the curvature radius of the cloud $R_c$ is given, we can determine the position of the cloud surface from Equation (10) and calculate the structure of the cloud using the iterative procedure described above. Since we assume that the cloud is in an equilibrium state, we adopt $R_c$, which minimizes the pressure gradient along the r-direction. We change $R_c$ from 0.02 pc to 0.11 pc in increments of 0.001 pc, and calculate the structure of the cloud for each $R_c$. Then, we integrate the deviation of the total pressure $P_{\text{tot}}(r,z)$ from the average total pressure over all cells at the same $z$ coordinates $P_{\text{ave}}(z)$.

$$\frac{\int |P_{\text{tot}}(r,z) - P_{\text{ave}}(z)|/P_{\text{ave}}(z) |dV}{\int dV}.\tag{36}$$

We adopt the structure of the cloud for which this value is minimized.

4. RESULTS

We present the results of our numerical models in this section. Model parameters of the run are summarized in Table 1. To compare with our observational results, intensities of the incident ionizing UV and FUV radiation were determined to correspond to those expected in the region where SFO 22 is located. Since the spectral type of the primary exciting star of SFO 22 is O7V, we adopted the values of log $S_{\text{UV}} = 48.76$ s$^{-1}$ and log $S_{\text{FUV}} = 48.76$ s$^{-1}$ as the UV and FUV photon luminosities (Vacca et al. 1996; Diaz-Miller et al. 1998). These luminosities and the distance from the exciting star to SFO 22 of 6.5 pc give the incident ionizing UV flux of $F_I = 1.192 \times 10^{9}$ cm$^{-2}$ s$^{-1}$ and incident FUV flux of $G_0 = 94$ in terms of the Hating field $F_H = 2.1 \times 10^{12}$ cm$^{-2}$ s$^{-1}$ (Bertoldi & Draine 1996). We used these values in all models except model A. The number density of the cloud before undergoing compression by radiation-driven implosion was assumed to be $n_0 = 10^3$ cm$^{-3}$ in all models. Some physical values obtained from our results are summarized in Table 2.

4.1. Effects of Strong FUV Radiation and Magnetic Field

In this subsection, we describe the results of the following three typical models A, B, and E2 to show how strong FUV radiation and magnetic field affect structures of clouds. Figure 9 shows the densities, the column densities, and the temperatures of these models. In model A, as a reference, we calculated the structure of the cloud without a magnetic field, assuming the strength of an average interstellar FUV radiation field of $G_0 = 1$. In model B, to see the effects of strong FUV radiation, we calculated the structure of the cloud assuming the strength of the FUV radiation expected in the region where SFO 22 is located, but the magnetic field effects were not included. In model E2, we included not only the effects of strong FUV radiation but also the magnetic field effects. The initial magnetic field strength $B_0$ and $\alpha$ were set to be 5 G and 0.75, respectively.

Figure 8 shows that the column density distribution of model A is much different from that of observed cloud. The peak column density of 1.26 $\times$ 10$^{22}$ cm$^{-2}$ is one order of magnitude higher than that of the observed cloud ($\sim 2 \times 10^{22}$ cm$^{-2}$). In addition, the slope of the column density profile is steeper than the observations. Figure 9 shows that the cloud has a nearly constant temperature of 20 K in model A. Since FUV radiation is not significant in this model, effective cooling keeps the dense region relatively cold.

Comparisons of model B to model A show that FUV radiation has little influence on the density and the thermal structures of the cloud. Although the cloud surface is heated near 30 K in model B, this warm surface layer is very thin. High density at the head region prevents CO molecules, which are main coolant of molecular gas, from photodissociation except for a thin surface layer. Isothermal gas is good approximation at inner

| Model | $a_0$ | $B_0$ (G) | $G_0$ | $F_I$ (cm$^{-2}$ s$^{-1}$) |
|-------|-------|-----------|-------|--------------------------|
| A     | 0     | 1         | 1.0   | $1.192 \times 10^7$      |
| B     | 0     | 0.75      | 1.0   | $1.192 \times 10^6$      |
| C1    | 0.25  | 25        | 94.0  | $1.192 \times 10^6$      |
| C2    | 0.25  | 45        | 94.0  | $1.192 \times 10^6$      |
| C3    | 0.25  | 60        | 94.0  | $1.192 \times 10^6$      |
| C4    | 0.25  | 80        | 94.0  | $1.192 \times 10^6$      |
| D1    | 0.50  | 7         | 94.0  | $1.192 \times 10^6$      |
| D2    | 0.50  | 15        | 94.0  | $1.192 \times 10^6$      |
| D3    | 0.50  | 25        | 94.0  | $1.192 \times 10^6$      |
| D4    | 0.50  | 45        | 94.0  | $1.192 \times 10^6$      |
| E1    | 0.75  | 2         | 94.0  | $1.192 \times 10^6$      |
| E2    | 0.75  | 5         | 94.0  | $1.192 \times 10^6$      |
| E3    | 0.75  | 10        | 94.0  | $1.192 \times 10^6$      |
| E4    | 0.75  | 25        | 94.0  | $1.192 \times 10^6$      |

Table 1: Model Parameters
region of the cloud. Figure 8 shows that the column density of model B is much higher than observations as well as model A. Although FUV radiation reduces the density than model A by factor of a few, it is not enough to reproduce observed low column densities. The shape of the cloud slightly differs from model A. Strong FUV radiation enhances thermal pressure at the head region and makes the curvature radius at the cloud tip larger than that of model A. Moving to the tail side, the differences of the density and the column density from those of model A become larger. As a result, the slope of the column density profile of model B is steeper than that of model A.

Comparisons of model E2 to model A and model B show that the magnetic field reduces the density of the cloud. Figure 9 shows that the density and column density of model E2 at the head region are one order of magnitude lower than those of models A and B. As shown in 4.2, magnetic pressure is dominant at $z > -0.4$ pc in model E2. Additional support due to magnetic pressure makes the density of the cloud lower than models without a magnetic field. The warm surface layer of model E2 is thicker than that of model B, because lower density at the head region allows FUV radiation to penetrate deeper inside the cloud. Figure 8 shows that the slope of the column density profile of model E2 is flatter than those of models A and B. The column density profile of model E2 shows better agreement with that of the observed cloud than the other two models.

4.2. Dependence on the Density Dependence of Magnetic Field Strength

In this subsection, we present a comparison of three models, C2, D2, and E2, to show how the value of exponent $\alpha$ in Equation (9) affects the results. The values of $\alpha$ and $B_0$ in models C2, D2, and E2 were set to be 0.25 and 45 $\mu$G, 0.50, and 15 $\mu$G, and 0.75 and 5 $\mu$G, respectively. The comparison of these models reveals that the value of $\alpha$ influences the structure of cloud.

As can be seen from Figure 8, although these three models have similar maximum values of column density of $\sim 2 \times 10^{22}$ cm$^{-2}$, the column density profiles of these models are qualitatively different. The model with a smaller value of $\alpha$ has a steeper column density profile at the head region ($z > -0.2$ pc) and has a flatter column density profile at the tail region ($z < -0.3$ pc). In model C2, the slope of the column density profile becomes flatter moving to the tail side. The opposite trend is observed in model E2. The slope of the column density profile becomes steeper moving to the tail side. Contrary to models C2 and E2, the slope of the column density profile is nearly constant through the entire region in model D2.

Figure 10 shows the magnetic field strength and plasma beta, which is defined as the ratio of thermal pressure to magnetic pressure, in these models. Although these three models have similar magnetic field strengths of $\sim 150$ $\mu$G at the cloud tip, the magnetic field strength decreases more quickly moving to the tail side in the model with the larger value of $\alpha$. The distribution of the plasma beta in the cloud qualitatively changes whether or not $\alpha$ exceeds 0.5. As can be seen from Equations (7) and (9), the thermal pressure and the magnetic pressure are proportional to $\rho$ and $\rho^{2\alpha}$, respectively. When $\alpha$ is larger than 0.5, magnetic pressure increases faster than thermal pressure with increasing density, and magnetic pressure becomes dominant in the dense region. When $\alpha$ is smaller than 0.5, by contrast, thermal pressure becomes dominant in the dense region. In model C2 in which $\alpha = 0.25$, the plasma beta is larger than unity in the dense head region and decreases the moving to the tail side. Thus, the thermal pressure is dominant at the head region; the magnetic pressure is dominant at the tail side. In model E2 in which $\alpha = 0.75$, the opposite trend is observed. The magnetic pressure is dominant at the head region; the thermal pressure is dominant at the tail side. In model D2 in which $\alpha = 0.5$, the plasma beta is nearly constant in the entire cloud because the magnetic pressure and the thermal pressure increase at the same rate with increasing density.

4.3. Dependence on Initial Magnetic Field Strength

In this subsection, we describe general trends which arise when the initial magnetic field strength $B_0$ is changed. In Figures 11 and 12, maximum values of the number density and

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**Table 2**

Summary of Numerical Results

| Model | $R_\alpha$ (pc) | $T_{\text{tip}}$ (K) | $n_{\text{H}_2,\text{max}}$ (cm$^{-3}$) | $N_{\text{H}_2,\text{max}}$ (cm$^{-2}$) | $B_{\text{max}}$ ($\mu$G) | $M_\text{c}$ ($M_\odot$) |
|-------|-----------------|---------------------|--------------------------------------|--------------------------------------|----------------------|--------------------------|
| A     | $7.6 \times 10^{-2}$ | 19.5 | $4.48 \times 10^5$ | $1.26 \times 10^{23}$ | $10^{16}$ | $61.3$ |
| B     | $9.4 \times 10^{-2}$ | 28.9 | $4.19 \times 10^5$ | $1.27 \times 10^{23}$ | $10^{16}$ | $54.8$ |
| C1    | $7.0 \times 10^{-2}$ | 30.3 | $2.61 \times 10^5$ | $5.65 \times 10^{22}$ | $119$ | $24.1$ |
| C2    | $4.1 \times 10^{-2}$ | 29.5 | $1.07 \times 10^5$ | $1.61 \times 10^{22}$ | $172$ | $5.59$ |
| C3    | $3.2 \times 10^{-2}$ | 27.2 | $5.35 \times 10^4$ | $6.36 \times 10^{21}$ | $192$ | $2.03$ |
| C4    | $2.7 \times 10^{-2}$ | 24.1 | $2.27 \times 10^4$ | $2.15 \times 10^{21}$ | $208$ | $0.653$ |
| D1    | $8.2 \times 10^{-2}$ | 30.3 | $1.81 \times 10^5$ | $5.33 \times 10^{22}$ | $133$ | $27.7$ |
| D2    | $7.1 \times 10^{-2}$ | 27.5 | $5.75 \times 10^4$ | $1.81 \times 10^{22}$ | $161$ | $10.4$ |
| D3    | $6.7 \times 10^{-2}$ | 24.2 | $2.39 \times 10^4$ | $7.17 \times 10^{21}$ | $173$ | $4.20$ |
| D4    | $6.5 \times 10^{-2}$ | 21.2 | $7.83 \times 10^3$ | $2.27 \times 10^{21}$ | $178$ | $1.35$ |
| E1    | $9.0 \times 10^{-2}$ | 30.1 | $1.42 \times 10^5$ | $5.17 \times 10^{22}$ | $139$ | $28.4$ |
| E2    | $8.9 \times 10^{-2}$ | 26.9 | $4.87 \times 10^4$ | $2.05 \times 10^{22}$ | $155$ | $13.0$ |
| E3    | $8.8 \times 10^{-2}$ | 23.8 | $2.08 \times 10^4$ | $8.77 \times 10^{21}$ | $164$ | $5.81$ |
| E4    | $8.7 \times 10^{-2}$ | 20.9 | $6.35 \times 10^3$ | $2.65 \times 10^{21}$ | $168$ | $1.79$ |

Notes.

a Temperature at cloud tip.

b Maximum value of number density of H$_2$.

c Maximum value of column density of H$_2$.

d Maximum value of magnetic field strength.

* Total cloud mass.
the magnetic field strength are plotted as a function of initial magnetic field strength $B_0$, respectively. As shown in Figures 9 and 10, the number density and the magnetic field strength reach their maximum values near the cloud tip, when the effects of FUV radiation are not significant. We focus on the low plasma regime and consider these maximum values as values at the cloud tips.

We can obtain the asymptotic behavior of the number density in the low plasma beta regime by neglecting thermal pressure. From Equations (7) and (9), the number density is expressed as

$$n = n_0 \left(\frac{8 \pi P_{\text{tot}}}{8 \pi P_{\text{tot}}}\right)^{1/2 \alpha} B_0^{-1/\alpha},$$

(37)

where we neglect the first term in the right-hand side of Equation (7) because we assume that the magnetic pressure is dominant. The total pressure $P_{\text{tot}}$ at the cloud tip is given by substituting $\theta = 0$ into Equation (13). Therefore, using the relation of $F_{\text{UV}} = F_i/q$, we obtain the number density at the
cloud tip as

\[ n_{\text{tip}} = n_0 \left( \frac{16\pi \mu m_{\text{HC}} F_i}{q} \right)^{1/2\alpha} B_0^{-1/\alpha}. \]  \hspace{1cm} (38)

This relation shows that the density at the cloud tip is proportional to \( B_0^{-1/\alpha} \) in the low plasma beta regime. The maximum number densities of our numerical models approach lines representing this analytic asymptotic value as \( B_0 \) increases (see Figure 11). We adopted the minimum value of \( R_c \) for models with each \( \alpha \) to calculate \( q \) in Equation (38), because the curvature radius at the cloud tip \( R_c \) decreases with increasing of \( B_0 \). We used the value of \( R_c = 0.027 \) pc for models with \( \alpha = 0.25 \), \( R_c = 0.065 \) pc for models with \( \alpha = 0.50 \), and \( R_c = 0.087 \) pc for models with \( \alpha = 0.75 \). The estimate value of the maximum number density of SFO 22 is also plotted in this figure. Dividing the maximum value of the observed column density \( 1.89 \times 10^{22} \text{ cm}^{-2} \) by the cloud width of 0.26 pc gives a rough estimate value of \( n_{\text{obs}} = 2.36 \times 10^4 \text{ cm}^{-3} \). From this figure, it is inferred that SFO 22 had an initial magnetic field strength of several to \( \sim 90 \mu \text{G} \), if the value of \( \alpha \) is from 0.25 to 0.75.

We can also obtain the asymptotic behavior of the magnetic field strength in the low plasma beta regime. Substituting Equations (26) and (38) into Equation (9) gives the magnetic field strength at the cloud tip as

\[ B_{\text{tip}} = \left( \frac{16\pi \mu m_{\text{HC}} F_i}{q} \right)^{1/2}. \]  \hspace{1cm} (39)

This relation shows that the magnetic field strength at the cloud tip is a function of the curvature radius of the cloud at the tip \( R_c \) and the incident ionizing photon flux \( F_i \), but is independent of the initial magnetic field strength \( B_0 \) and the initial number density \( n_0 \). As the initial magnetic field strength \( B_0 \) increases, the magnetic field strength at the cloud tip approaches this asymptotic value. Equation (39) gives asymptotic values of 212 \( \mu \text{G} \) for models with \( \alpha = 0.25 \), 180 \( \mu \text{G} \) for models with \( \alpha = 0.50 \), and 170 \( \mu \text{G} \) for models with \( \alpha = 0.75 \). The maximum magnetic field strengths of our numerical models asymptotically approach this value at large \( B_0 \) (see Figure 12).

5. DISCUSSION

5.1. Comparison between Observations and Numerical Models

We developed a numerical model for a photoevaporating cloud which is in a quasi-stationary equilibrium state, assuming that the pressure gradient of the cloud balances the inertia force caused by acceleration due to the back reaction of the photoevaporation flow. As shown in Section 4.1, the observed density structure of BRC SFO 22 cannot be explained by the reference model (model A) in which either the effects of strong FUV radiation or the effects of magnetic field were not included. The column density of the reference model is one order of magnitude higher than that of the observed cloud. The observed lower column density implies that the pressure of the observed cloud is higher than that of the reference model. There are two possible explanations for this large difference of density structures between the observed cloud and the reference model. One explanation is that heating due to strong FUV radiation from the exciting star warms the cloud, and hence enhanced thermal pressure makes the cloud reach an equilibrium state with lower density than the reference model. Another explanation is that additional pressure due to the magnetic field makes the cloud reach an equilibrium state with lower density than the reference model.

Comparisons between the reference model and numerical model including the effects of strong FUV radiation (model B) show that strong FUV radiation has little influence on the structure of the cloud. Although strong FUV radiation slightly reduces the density and the column density of the cloud, the column density is much higher than that of the observed cloud. The small difference from the reference model suggests that the heating due to the FUV does not affect the structure of the cloud at least in SFO 22. To affect the structure of the cloud, the photoelectric heating needs to be the dominant heating process, i.e., \( \Gamma_{\text{pe}}/\Gamma_{\text{cr}} > 1 \). For a rough estimation, let us approximate the efficiency of photoelectric heating \( \epsilon \) expressed by Equation (30) by a constant value of \( 4.87 \times 10^{-2} \). From Equations (29)–(31), and the relation of \( \tau_{\text{UV}} = 2.5 A_V \), the ratio of the photoelectric heating rate to the cosmic ray heating rate...
is written as

$$\frac{\Gamma_{pe}}{\Gamma_{cr}} \simeq 43 \, G_0 \exp(-2.5A_V).$$  \hspace{1cm} (40)$$

Therefore, visual extinction of the cloud along the direction to the exciting star needs to be smaller than the critical value

$$A_{V, cri} = \frac{\ln(43G_0)}{2.5}.\hspace{1cm} (41)$$

Applying this equation to SFO 22 gives the critical value $A_{V, cri}$ as 3.3. The total mass traced by the $^{13}$CO emission and width of SFO 22 give a rough estimate of the visual extinction of SFO 22 as

$$A_{V, SFO22} \simeq X_{A_V} \frac{12.0 \, M_\odot}{\mu m_\text{H}_\text{II}(0.13 \text{ pc})^2}.$$  \hspace{1cm} (42)

This gives the value of 15.4. This larger value of $A_{V, SFO22}$ compared to $A_{V, cri}$ indicates that the heating due to FUV radiation affects only near the cloud surface. This discussion based on a rough estimation is consistent with our numerical results.

Comparisons between the reference model and numerical model including magnetic field effects show that the magnetic field strongly affects the structure of the cloud. From results of models C2, D2, and E2, an initial magnetic field strength of 5–45 $\mu$G is required to reproduce the observed column density of $\sim2.0 \times 10^{22}$ cm$^{-2}$ depending on the value of $\alpha$. On the other hand, magnetic field strengths in molecular clouds are measured by Zeeman effects. Crutcher et al. (2010) statistically analyzed samples of clouds with Zeeman observation in order to infer the distribution of the total magnetic field strength in the samples. According to their analysis, molecular clouds with the density of $\sim10^3$ cm$^{-3}$ have magnetic field strength of a few to several tens of $\mu$G. This coincidence of magnetic field strengths between numerical models and observations shows that the observed column density of SFO 22 is naturally explained by magnetic field effects.

### 5.2. Magnetic Field Configurations in BRCs

As shown in 4.2, the structure of BRC strongly depends on the value of $\alpha$ in Equation (9). The slope of the column density profile at the head region becomes steeper with decreasing $\alpha$. The slope of the column density profile at the tail region shows an opposite dependence on $\alpha$. Since this parameter represents how much the magnetic field is trapped in the gas during the compression, our numerical results imply that the direction of the magnetic field affects the evolution of BRCs. When the magnetic field is parallel to the direction of UV radiation, the value of $\alpha$ is close to 0. On the other hand, when the magnetic field is perpendicular to the direction of UV radiation, the value of $\alpha$ is close to 1. Since the results of model E2, in which $\alpha$ was set to be 0.75, show the best agreement with observations, the magnetic field in SFO 22 is thought to be nearly perpendicular to the UV radiation. However, deviation from observations can be seen at the tail region. The slope of the column density of model E2 is steeper than that of the observed cloud at the tail region (see Figure 8). This difference of column density profiles implies the possibility that the value of $\alpha$ at the tail region is smaller than the head region. Mackey & Lim (2011) performed three-dimensional MHD simulations and found that for weak and medium magnetic field strengths an initially perpendicular field is swept into alignment with the tail during dynamical evolution. Their results may explain the reason why the value of $\alpha$ is small at a tail region. Figure 13 shows the schematic figure of the magnetic field configuration in SFO 22 suggested by comparisons between our numerical results and observations. The possible scenario is as follows. The magnetic field in SFO 22 was initially perpendicular to the UV radiation from the exciting star. Then, compression due to radiation-driven implosion made the magnetic field close to parallel to the UV radiation at the tail region.

Very few attempts have been made to observationally study the magnetic fields of BRCs. Sridharan et al. (1996) performed optical polarimetry observations toward CG 22 and reported that the magnetic field is parallel to its tail. Their rough estimate gives a magnetic field strength of $\sim30$ $\mu$G. It is comparable to the magnetic field strength obtained by our numerical models (see Figure 10). Other optical polarimetry observations by Bhatt (1999) showed that the magnetic field in CG 30–31 is found to be nearly parallel to the cometary tails. Observational studies on the relations between the density structures and magnetic field configurations in BRCs are required to reveal the magnetic field effects on the evolution of BRCs.

### 6. CONCLUSIONS

Using the Nobeyama 45 m telescope, we observed BRC SFO 22 in the $^{12}$CO ($J = 1$–$0$), $^{13}$CO ($J = 1$–$0$), and C$^{18}$O ($J = 1$–$0$) lines. Observed column density profiles were compared with those of numerical models for a photoevaporating cloud.
in quasi-stationary equilibrium state in order to investigate how the magnetic field and heating due to strong FUV radiation from the exciting star affect structures of BRCs. We summarize our main conclusions as follows:

1. From our radio observations, the column density profiles of SFO 22 along the line to its exciting star are nearly flat with the column density of \( \sim 10^{22} \) cm\(^{-2}\).

2. Strong FUV radiation from the exciting star has little influence on the structure of SFO 22. Although enhanced thermal pressure due to strong FUV radiation slightly reduces the density of the cloud, its effects are not enough to reproduce the observed density structure of SFO 22.

3. The magnetic field strength and direction of the magnetic field strongly affect the structure of BRCs. The numerical model with an initial magnetic field strength of 5 \( \mu \)G shows the best agreement with the observations. When the magnetic field is nearly parallel to the UV radiation from the exciting star, the cloud has a steep column density profile at the head region and a flat column density profile at the tail region. When the magnetic field is nearly perpendicular to the UV radiation, the column density profile shows the opposite trend.

In this paper we only focus on the quasi-stationary equilibrium phase of the radiation-driven implosion model, and we will discuss the implosion phase in a subsequent paper. We also plan a further study using MHD simulation to establish a more realistic evolutionary model of BRCs.

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