Zeeman Spectrum from a Magnetically Triggered Jet

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Abstract

We consider the conclusive evidence of magnetically triggered jets. Astrophysical jets have strong morphological similarities in spite of their variety of physical scales. We consider the YSO jet as the typical case of astrophysical jet systems. In particular, the base region of the YSO jets is focused because our main interest is in the jet launching mechanism. We numerically examined the Zeeman spectrum when the model structure of magnetically triggered jets was assumed. The Zeeman spectrum represents the combination effects of the flow velocity and structure of magnetic fields. We found that the physical evidence of the helical field structure of jets is imprinted in the Stokes V spectrum as an “M”-shaped line profile. The detection of this characteristic feature of the Zeeman spectrum will constrain the MHD models of jets in the near future.

Key words: magnetic fields — magnetohydrodynamcis: MHD — polarization — stars: winds, outflows

1. Introduction

One of characteristic and important features of astrophysical jets, such as AGNs, microquasars and YSOs, is the collimation of jetted flow. For example, we can observe that the YSO jet HH 211 is collimated over ~ 10^4 AU, AGN jet M 87 is ~ 2000 pc, and microquasar LS 5039 is ~ 87 AU (Hirano et al. 2006; Gracia et al. 2005; Paredes et al. 2002).

The most promising mechanism for collimating the jet is a magnetic tension force, which is expected to act in a magnetically driven jets (MHD model: Uchida & Shibata 1986; Shu et al. 1995). The prediction from the MHD model is that the jet flow should rotate around the flow axis with increasing distance from the central objects. This is because the tangled magnetic field is untwisted and the helical velocity of the flow increases along with stretching of the jet.

Recent HST observations of the rotation of the jetted flow in YSO HH 211 support the MHD model, and make it as the most promising one for explaining the features of the astrophysical jet system (Bacciotti et al. 2002). However, the direct link between the tangled magnetic field and the rotation of flow has not been detected observationally at all.

Clarification of the connection between the rotation and field structure is also very important to understand the jet triggering mechanism. When the magnetically driven mechanism is effective, the field configuration should satisfy the criterion between the rotation velocity and the field strength to accelerate the jet in its base region, which is near from the central objects (see figure 1, Blandford & Payne 1982; Donati et al. 2005). In order to link the field structure and the flow velocity and to reveal the jet launching mechanism, we need an observational indicator for reflecting the jet structure specifically.

In this paper, we consider the Zeeman-splitting effects that would appear in the line profile as a candidate for indicating the flow and field structures at the base region of astrophysical jets. In particular, the YSO (Young Stellar Objects) jet is focused, since it is very near from us, and thus the observational feasibility is expected. A simple model structure of the MHD jet is adopted here for calculating the Zeeman spectrum.

In section 2, the physical assumption for the jet structure and the numerical method to calculate the Zeeman profile of polarized line emission are described. The results of our calculation are presented in section 3. In section 4, we discuss the observational applications and finally summarize our paper.

2. Numerical Methods

The rotation of the jet is imprinted as the Doppler shift of the line profile, and the magnetic field makes the line profile split due to the Zeeman effect, as is well known. In order to connect the field configuration and the rotation of the flow, the line profile suffering the Zeeman splitting was studied in the context of MHD jet model. Here, we describe the simple jet model used in this paper and the calculation method for the Zeeman line profile.

2.1. Jet Model

The situation considered in this paper is summarized in figure 1 schematically. For simplicity, we adopt a one-dimensional model of an MHD jet studied by Kudoh and Shibata (1997) (hereafter KS97). We take the magnetic field,
velocity, density and so on from KS97. This model well represents the basic properties of the jet, such as collimation and rotation. In figure 3 of KS97, we find that $V_{\phi}(z)$ and $B_{\phi}(z)$ represent the rotation structure of the flow, where the subscript of $\phi$ represents the toroidal components and $z$ the height from the disk midplane.

As the boundary conditions of the temperature, density and field strength at the footpoint of the jet, we set $T_0 = 1000 \text{ K}$, $n_0 = 10^{13} \text{ cm}^{-3}$, $B_{p0} = 10 \text{ G}$, respectively. Also, $r_0 = 15 R_{\odot}$ is the radius of the jet at the footpoint. Here, subscript $p$ denotes the poloidal component of magnetic fields and the subscript of zero represent quantities of the footpoint of the jet. We also assume the terminal velocity of the jet to be $100 \text{ km s}^{-1}$ and an adiabatic index of $\gamma = 1.05$.\footnote{$\gamma = 1.05$ of the model is assumed according to the private communication to Dr. Kudoh since this does not appear in KS97.}

The structure of magnetic fields used throughout this paper is configured as follows. First of all, we selected $B_{p0}$ as a boundary condition. Once $B_{p0}$ was selected, $B_{p}(z)$ was calculated owing to two conservation laws of $B_{p} \Sigma = \Phi = \text{const}$, and $\Sigma \propto r^2$. Here, $\Sigma$ is a cross section of a flux tube (as noted in KS97). Finally, $B_{\phi}(z)$ is given from the structure of $B_{p}(z)$ via $B_{\phi}/B_{p}(z)$ in figure 3b of KS97. The fiducial model is for the case $B_{p0} = 10 \text{ G}$ and is represented by a superscript $f$. We are interested in the base region of the jet because the jet triggering mechanism is imprinted in the configuration of the field around there. We thus focus on the Zeeman effect at the limited region within the MHD fast point (see figure 1). The overall properties of the MHD flow adopted in this paper is maximally simplified. Such a rough treatment is sufficient to study the qualitative features of our interest.

Since the distance to the jet from us and the angle between the jet axis and our line of sight (see figure 1), we select those of HH 211 one of the nearest YSO jet, that is, $D = 315 \text{ pc}$ (see McCaughrean et al. 1994) and $\Theta = 80^\circ$ (Hirano et al. 2006).

### 2.2. Zeeman Effect

The Zeeman effect is the splitting of the spectral lines into multiple right- or left-circularly polarized components due to the external magnetic field. In a realistic situation, the splitting patterns are very complicated (e.g., Shinnaga & Yamamoto 2000). It is, however, known that the multiple splitting can be well approximated by a simple triplet when $\nu_2 \ll \nu_{\text{FWHM}}$. Here, $\nu_2$ is the frequency difference among the energy levels of the fine structure within $\Delta M = 1$ or $\Delta M = -1$, and $\nu_{\text{FWHM}}$ is the full-width of the half maximum (FWHM) of the spectral line due to the thermal motion. We know $\nu_2$ is always much smaller than $\delta \nu$, which is the typical frequency shift between the right- or left-circularly polarized components and fixed. For varying the field strengths, we multiply the physical parameters $b_p$ and $b_\phi$ by those of the fiducial model,

$$b_p = B_p(z)/B_{p0}(z), \quad b_\phi = B_\phi(z)/B_{\phi0}(z).$$

To examine the effect of the field structure, the following three cases are calculated: (1) Varying $B_p(z)$, while $B_\phi(z)$ is fixed; (2) Varying $B_\phi(z)$, while $B_p(z)$ is fixed; (3) Varying the magnetic field strength $B$, while field direction $B_\phi/B_p(z)$ is fixed. For varying the field strengths, we multiply the physical parameters $b_p$ and $b_\phi$ by those of the fiducial model,

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the frequency in no external magnetic field. Since $\delta v \sim v_{\text{FWHM}}$ ($\sim 0.7 \, \text{km s}^{-1}$) in this paper, we find that $v_z \ll v_{\text{FWHM}}$ at any $z$. We thus consider the triplet pattern.

The formulation of the triplet analysis is summarized precisely in Sault et al. (1990), then we show only the result:

$$I_{\pm}(v) = \frac{1}{4} [I_0(v + \delta v) + (\cos \theta \mp 1) I_0(v - \delta v) + 2 \sin^2 \theta I_0(v)],$$

(2)

where $I_+$ and $I_-$ are oppositely the polarized flux obtained by spectroscopy, and they are relating to $I$ of Stokes parameters as $I = (I_+ + I_-)/2$, and $I_0$ is the Stokes $I$ spectrum without external magnetic field. Here, $\theta$ is the angle between the magnetic field and the line of sight, and is calculated from $\Theta = 80^\circ$.

When we estimate the field strength, the Stokes $V$ is also needed and is related to the Stokes $I$ via the relation $V = (I_+ - I_-)/2$ (see Sault et al. 1990). We then get both of $I$ and $V$ simultaneously once the right- and left-polarized emissions are detected.

To utilize equation (1), we must estimate $\delta v \approx M_X \times B$, where the proportional constant of $M_X$ is eigen quantity of a selected molecule of X.

To check our numerical method, we confirm the Stokes $V$ parameter of the normal Zeeman pattern with coming magnetic field in the left panel of figure 2. The vertical axis is the flux described in arbitrary units, and the horizontal axis is the LSR velocity (velocity of the Local Standard of Rest) in arbitrary units. Since the helical structure of the field is never considered, the famous characteristic sideways profile of “S” in the $V$ parameter of the Zeeman effect is reproduced. Our numerical procedure is reasonable.

2.3. Zeeman Line

Millimeter interferometer studies of Class 0 YSOs have identified high-velocity SiO jet-like emission, possibly related to the primary proto-stellar wind (Codella et al. 2007; Guilloteau et al. 1992; Chandler & Richer 2001; Hirano et al. 2006; Palau et al. 2006). We consider the Zeeman effect of SiO $J = 5-4$ emission. The reasons are:

1. Compared with the CO or $\text{H}_2$ emission line, the SiO emission line traces the more collimated part of the jet

   \begin{figure}[h]
   \centering
   \includegraphics[width=0.5\textwidth]{fig2.png}
   \caption{V spectrum of the Zeeman effect. We confirm sideways “S”. The vertical axis is the flux and horizontal axis is an LSR velocity. Both of the axes are described in arbitrary unit.}
   \end{figure}

(see Codella et al. 2007), and generally suffers minimal contamination from infalling envelopes or swept-up cavities (Guilloteau et al. 1992; Hirano et al. 2006). The SiO $J = 5-4$ line is therefore appropriate for verifying our simple consideration.

2. The SiO $J = 5-4$ line can be received in band-6 of ALMA (217.105 GHz).

3. The SiO abundance in quiescent gas within cloud cores is $< 10^{-12}$ relative to molecular hydrogen (Irvine et al. 1987; Ziurys et al. 1989), which can rise to as high as $\sim 10^{-5}$ (Chandler & Richer 2001) and $\sim 10^{-6}$ (Martín-Pintado et al. 1992) in outflows.

In this paper, we assume that the SiO lines are optically thin (e.g., Nisini et al. 2002, 2007, Gibb et al. 2004). However, the recent observations indicate that the SiO lines are optically thick (Cabrit et al. 2007). According to Cabrit et al., the required conditions for the SiO lines being optically thick are that the shock velocity and pre-shock density become an order of $O(10^3) \, \text{cm}^{-3}$ and $O(10^5) \, \text{cm}^{-3}$, respectively. The region where this condition would be approved is far from the center of the YSO jet, in other word, $O(100) \, \text{yr}$ after the jet launching. Our interest is in the very localized region within $\sim 10 \, \text{AU}$ ($\sim 0.02 \times 315 \, \text{pc}$) from that center (see figure 1). We pay attention to the much earlier epoch than 100 yr. We can thus assume that the SiO lines are optically thin at an early epoch before the SiO lines become optically thick.

It is sometimes stressed that research on the Zeeman effect of a nonmagnetic molecular transition, like SiO, is not practical because the frequency shift owing to the Zeeman effect is vanishingly small compared with the Doppler line width. However, the characteristic sideways profile of “S” in the $V$ parameter of the Zeeman effect itself being negligible (e.g., Elitzur 1996).

2.4. Helical Effect

In the framework of magnetically triggered jets, both the velocity and the magnetic field are in the helical configuration. Here, we analyze those helical effects on the Zeeman profile. The essential feature of the helical effects of the velocity and the magnetic fields are displayed in figure 3. The vertical axes mean the flux depicted in arbitrary units because the flux changes according to the physical parameters characterizing the MHD jets. The horizontal axes are an LSR velocity in units of km s$^{-1}$. In both panels, the dashed line is the circularly polarized component, $I_+$, the dotted line is the oppositely polarized component, $I_-$, and the solid line means the total flux, $I = I_+ + I_-$. Note that, the upper panel of figure 3a, $I_+$ is overplotted on $I_-$. We consider the rigidly rotating jet with a constant density at all radii for simplicity. The $z$-dependence of the density is in figure 3b of KS97. Figure 3a shows the $I$ and $V = (I_+ - I_-)/2$ spectra from a rotating jet at a fixed height from a region sliced at a fixed height $z$, without a magnetic field. Figure 3b is the same, but with a magnetic field.

These panels show the spectrum from a region sliced at a specific height of $z$, the radius of which is much smaller than the beam size of ALMA ($\sim 0.02$). We need to superpose the spectrums at each $z$ in order to obtain the final line profiles, which are considered in section 3.
Figure 3a represents the pure effect of the helical velocity field because of no magnetic fields. We can evaluate the thermal broadening of the line profile as $\delta v \sim 0.7 \text{km s}^{-1}$ which is much smaller than the line-extension due to the helical effect of the jets ($V_\phi = 10^4 \text{km s}^{-1}$). Therefore, the broadening of the Stokes $I$ line profile found in figure 3a originates from the effect of the helical velocity field. Since the jet is assumed to rotate rigidly, the profile would not be Maxwellian.

The effect of the helical magnetic field is reflected in figure 3b. We find a characteristic feature for the case considering the effect of the helical magnetic field as the “M”-shaped line profile in the $V$ spectrum. The “M”-shape originates from the spatially reversed direction of $B_\phi$ at the flow axis (see figure 1). From the left (or right) part of the jetted flow, we can see the coming line-of-sight component of the magnetic field. Thus, the Stokes $V$ spectrum becomes like figure 2. On the other hand, the going line-of-sight component of the magnetic field is seen from the right (or left) part of the flow. The Stokes $V$ spectrum thus has a shape like the reversal of figure 2. The superposition of the lines from the left and right parts of the flow brings the “M”-shaped spectrum.

2.5. Flux of the Line Emission

Since the purpose of this paper is to find the characteristic properties of the Zeeman spectrum from rotating MHD jets, the flux of the line emission is just an order estimation. Here, we normalize the number density of SiO by $n \times 10^{-5}$, where $n$ is the number density of all the particles. A tentative coefficient of $10^{-5}$ is chosen, since Chandler and Richer (2001) allows the fraction of SiO to be $6 \times 10^{-6}$, which is the maximally expected one.

The cooling function of SiO is then denoted as

$$n^2L = \Delta E (J = 5–4) A_{\text{SiO}} (J = 5–4) n_{\text{SiO}} (J = 5),$$  \hspace{1cm} (3)

where $\Delta E (J = 5–4)$ is the energy difference of the SiO $J = 5–4$ transition and $n_{\text{SiO}} (J = 5)$ is the number density of SiO molecules in the state of $J = 5$. Since SiO density is less than the critical density, it is simply estimated from the Boltzmann distribution,

$$n_{\text{SiO}} (J) \approx n_{\text{SiO}} g_J \exp \left( -E_J/kT \right)/Z,$$  \hspace{1cm} (4)

where $g_J = 2J + 1$ is the statistical weight, and $Z$ is the partition function, which is approximately $kT/\epsilon_0$ for $E_J = \epsilon_0 J^2$. The total flux expected to reach us, $F$, is calculated from the equation $F = V n^2 L / D^2$, where $V$ is the emitting volume. In this paper, we adopt $V$ as $15R_\odot \times 15R_\odot \times 0.02 \times D$, which corresponds to ALMA’s beam size of $\sim 0.02$. In the case considering HH 211 as the observational object, its distance from us becomes $D = 315 \text{pc}$.

We can not obtain accurate physical quantities characterizing the molecular property of SiO, such as the spontaneous transition rate from $J = 5$ to $4$ of the SiO molecule, $A_{\text{SiO}} (J = 5–4)$, and eigen quantity, $M_{\text{SiO}}$. We thus adopt the normalized rate of $A_{\text{SiO}}$ by that of $A_{\text{CO}} = 1.30 \times 10^{-5}$ (Chandra et al. 1996) in this paper, that is $A_{\text{SiO}} (J = 5–4) / A_{\text{CO}} (J = 5–4)$. In addition, we use $M_{\text{CO}}$ as a substitute for $M_{\text{SiO}}$. It is a small problem using the value of CO physically within the order calculation of the line flux, because the molecular structure of SiO is very similar to that of CO. Moreover, the “M”-shape feature in the line spectrum appears in spite of the size of $M_{\text{SiO}}$, because $\delta v$ is always estimated as being small. Thus, the main conclusion from our calculations is not altered depending on its value.

3. Results

Figure 4 shows our numerical calculation of the Zeeman spectrum from the MHD jet model in the cases with different field configurations. As described in subsection 2.1, figure 4f is the fiducial model with $B_p = 10 \text{G}$ and $B_\phi / B_p (z)$ is the one in figure 3b of KS97 (the case $b_\phi = b_\rho = 1.0$). In panel (a),
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**Fig. 4.** Stokes $I$ and $V$ spectrum. The dashed, dotted and solid lines are the same as in figure 3. Panel (f) is a fiducial model. In panel (a), $b_p = 0.5$ and $b_\phi = 1.0$. In panel (b), $b_p = 1.0$ and $b_\phi = 0.5$. In panel (c), $b_p = b_\phi = 0.5$. $b_p$ and $b_\phi$ are defined in subsection 2.1.

$b_p = 0.5$ and $b_\phi = 1.0$. In panel (b), $b_p = 1.0$ and $b_\phi = 0.5$. In panel (c), $b_p = b_\phi = 0.5$; that is, field strength, $B(z)$, is half of that in the fiducial model, and the field direction, $B_\phi / B_p(z)$, is fixed; $b_p$ and $b_\phi$ are defined in subsection 2.1.

The upper and lower panels in each figure set show the Stokes $I$ and $V$, respectively. These spectra were calculated by using the SiO $J = 5–4$ line, and the parameters of HH 211 ($D \sim 315$ pc, $\Theta = 80^\circ$) are the same as the illustrative examples of figure 3. Unlike figure 3, the spectra from all vertical heights $z$ are summed up in these figures. The integrated area of $z$ is restricted to be within the range $10^{-1} - 10^3 r_0 / 0.02 \times D \sim 10^{14}$ cm. We don’t include the range of $0 – 10^{-1} r_0$ so as to avoid any confusion concerning the position of a central star. The vertical axes represent the flux in units of $\mu$Jy/beam and the horizontal axes the LSR velocity in units of km/s.

Note that in this paper we use $10^{-5} \times n$ in place of the number density of SiO $n_{SiO}$. In addition, the $J = 5–4$ transition rate of the CO molecule, $A_{CO}(J = 5–4) = 1.3 \times 10^{-5}$, is also substituted for that of SiO $A_{SiO}(J = 5–4)$. The practical SiO flux, $F_{SiO}$, is thus given by the following relation, with using the flux calculated in these figures, $F$: $F_{SiO} = F \times \left( \frac{n_{SiO}}{10^{-5} \times n} \right) \left[ \frac{A_{SiO}(J = 5–4)}{1.3 \times 10^{-5}} \right]$. (5)

Our main finding is the unusual Zeeman pattern in the $V$ spectrum for all cases. The “M”-shaped line profile is found in each panel as the characteristic feature of the $V$ parameter. It originates from the superposition of figure 3b, which displays an “M”-shaped $V$ profile from a region sliced at a vertical height, $z$. As far as the jet is magnetized and has helical structure, the $V$ profile must be “M”-shaped.

Specifically, we describe the characteristic properties of the “M”-shaped line profile. The two quantities are focused here: (1) the ratio of the first rise to the second one of the “M”-shaped profile; and (2) the width of the profile of the $V$ parameter. When we adopt $V_1$, $V_2$, and $V_3$, as shown in figure 4f, the
former is defined as $V_2/V_1$, and the latter is defined as the full width at half of $V_3$. Let us call these “M-ratio” and “M-width” in this paper, respectively.

In comparison with figures 4f and 4a, we find that the M-ratio of (a) is about 0.90, which is larger than $\sim 0.75$ of the M-ratio of (f). This indicates that the helicity along the flow is imprinted in the M-ratio. On the other hand, the M-width remains to almost be a constant of about 30 km s$^{-1}$.

Comparing models (f) and (b), the M-width of (f) is about 18 km s$^{-1}$, and was found to be smaller than that of (f), although M-ratio is not different. It is found from this result that the M-width means the degree of the line split owing to the field strength along the line of sight, which is nearly M-width means the degree of the line split owing to the field strength along the line of sight, which is nearly.

$V_2=V_1$

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$18kms^{-1}$, and was found to be smaller than that of (f), although $M$-ratio is not different. It is found from this result that the $M$-width means the degree of the line split owing to the field strength along the line of sight, which is nearly $B_\phi$ in the case of $\Theta \sim 90^\circ$. Expectedly, the $M$-width of (c), which is about $\sim 18km s^{-1}$, is smaller and the M-ratio, which is $\sim 0.90$, is larger than those of (f), respectively, since model (c) is a combination of models (a) and (b). We can recognize that the detection of the “$M$”-shaped line profile gives us information about the field-twisting degree of the YSO jets. Once the “$M$”-shaped profile of the Stokes $V$ spectrum is observed with sufficient resolution, we will constrain which theoretical model is adequate for the realistic jetted flow.

We comment about the asymmetry seen in the $I$ and $V$ spectra. This emerges due to $B_p$ and $V_p$. $B_p$ makes the magnitude of the line-of-sight components of the magnetic field at the left and right parts of the jetted flow different (the direction is also opposite due to $B_\phi$). See figure 1.) This difference makes the spectrum from a sliced region at each $z$ asymmetric (like figure 3b). Then, upon summing the spectrums at each $z$, $V_p$ brings a different Doppler shift at each $z$, and this makes the final profile more asymmetric. The combination of these two effects appears as the asymmetry of the profiles. In the case of $B_p(z)=0$ and $V_p(z)=0$ or $\Theta = 90^\circ$, the spectrum is completely symmetric because the line-of-sight component of $B_p(z)$ and $V_p(z)$ become zero.

4. Discussion and Summary

In this paper, we examine the Zeeman effect of the SiO $J=5–4$ line originating from the base of the MHD jet. We find that the helical structure of the flow and the field gives the Stokes $V$ spectrum an “$M$”-shaped profile. The “$M$”-shaped profile is sure to represent the physical information of the MHD jet: in the case with a fixed $B_\phi(z)$, the M-ratio decreases with $B_p(z)$, and the M-width decreases with $B_\phi(z)$ in the case with a fixed $B_p(z)$.

These strong relations are summarized in figure 5. The upper and lower panels of figure 5a show the $B_p(z)$-dependence of the M-ratio and the M-width (km s$^{-1}$) when $B_\phi(z)$ is fixed, corresponding to the case of figure 4a. Figure 5b show the $B_\phi(z)$-dependence when $B_p(z)$ is fixed, corresponding to the case of figure 4b. Figure 5c depicts the $B(z)$-dependence when the field direction, $B_\phi/B_p(z)$, is fixed, corresponding to the case of figure 4c. Note that the horizontal axes are normalized by the values of the fiducial model, which are, $b_p = B_p(z)/B_p^f(z)$ and $b_\phi = B_\phi(z)/B_\phi^f(z)$, respectively.

We can catch the reason for the relation between the M-ratio and $B_p(z)$ qualitatively, which is depicted in panel (a). The M-ratio is the value representing the asymmetry of profile, and $B_p$ is the factor that makes the profile asymmetric explained in section 3, so the M-ratio is affected by $B_p$. The reason for the relation between $B_\phi(z)$ and the M-width of panel (b) is almost the same as the normal Zeeman effect. In the normal Zeeman effect, the width of the $V$ spectrum is due to the strength of the magnetic field along the line-of-sight. We remember the field component along the line of sight is determined mainly from

![Figure 5](https://academic.oup.com/pasj/article-abstract/60/4/911/1399056/1399056)

**Fig. 5.** $B_p(z)$, $B_\phi(z)$ and $B(z)$-dependence of M-ratio and M-width (km s$^{-1}$) derived from each Stokes $V$ parameter. Referring to figure 4f, the M-ratio is defined as $V_3/V_1$ and the M-width as the full width at half of $V_3$. Panel (a): The $B_p(z)$-dependence of M-ratio and M-width (km s$^{-1}$) when $B_\phi(z)$ is fixed, corresponding to the case of figure 4a. Panel (b): The $B_\phi(z)$-dependence of them when $B_p(z)$ is fixed, corresponding to the case of figure 4b. Panel (c): The $B(z)$-dependence of them when the field direction $B_\phi/B_p(z)$ is fixed, corresponding to the case of figure 4c. The horizontal axes are normalized by the values of fiducial model, that are, $b_p = B_p(z)/B_p^f(z)$ and $b_\phi = B_\phi(z)/B_\phi^f(z)$, respectively.
because of $\Theta = 80^\circ$. Therefore, it is very trivial that the M-width is affected by the magnitude of $B_\phi(z)$. The discovery of the "M"-shaped line profile of the Stokes V parameter means the helical structure of the jet and the rotation of the flow simultaneously. Furthermore, this shows that the magnetic field plays a main role for confining the YSO jet.

The observed flux of HH 211 in Hirano et al. (2006) is $\sim 73 \text{ mJy beam}^{-1}$ at the peak at a beam of 1.7 $\times$ 0.9. Our results show an $\sim 3 \mu \text{Jy beam}^{-1}$ at 0.02 $\times$ 0.02; the flux is $\sim 1/24000$ at a beam size of $\sim 1/4000$. This indicates that our calculation is not so terrible. However, this calculated flux is undetectable by the present observational tools, and even by ALMA. The progress will make it possible to detect the "M" shape. Or perhaps a more appropriate jet than HH 211.

Finally, we comment on an insufficient point of our model. In changing the magnetic configuration of KS97's model to investigate the relations between $V$ and/or the M-ratio, we vary only the magnetic configuration in the way explained in subsection 2.1. The variables, such as the density, velocity and temperature, are postulated as being those satisfying the original distribution of KS97. Thus, our model in this paper is not sufficient. But, our results have a clear physical explanation, which is presented above. We are thus sure the results are reliable qualitatively.

Of course, further development of the model, observational and observational tools are necessary for quantitative discussions to determine which theoretical model is realistic. Especially, to distinguish the purely co-rotation model (e.g., Shu et al. 1994) and the extended disk wind model (e.g., Ferreira et al. 2000, 2006) is important. However, since we must know the field-twisting degree of the jets, we should apply our results to numerical simulations. Thus, in future work, we are planning to construct a further developed model of the "M" shape profile. Collating the restriction and the prediction of the MHD model (or other models) will bring great progress on understanding the physics of jets.

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