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A FAILED GAMMA-RAY BURST WITH DIRTY ENERGETIC JETS SPIRITED AWAY? NEW IMPLICATIONS FOR THE GAMMA-RAY BURST–SUPERNOVA CONNECTION FROM SN 2002ap

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ABSTRACT

The Type Ic supernova (SN) 2002ap is an interesting event with very broad spectral features like the famous energetic SN 1998bw associated with a gamma-ray burst (GRB) 980425. Here we examine the jet hypothesis from SN 2002ap recently proposed based on the redshifted polarized continuum found in a spectropolarimetric observation. We show that jets should be moving at about $0.23c$ to a direction roughly perpendicular to us, and the degree of polarization requires a jet kinetic energy of at least 5×10^{50} ergs, a similar energy scale to the GRB jets. The weak radio emission from SN 2002ap has been used to argue against the jet hypothesis, but we argue that this is not a problem because the jet is expected to be freely expanding and unshocked. However, the jet cannot be kept ionized because of adiabatic cooling without external photoionization or a heating source. We explored various ionization possibilities and found that only the radioactivity of ^{56}Ni is a plausible source, indicating that the jet is formed and ejected from the central region of the core collapse, not from the outer envelope of the exploding star. Then we point out that, if the jet hypothesis is true, the jet will eventually sweep up enough interstellar medium and generate shocks in a few to 10 yr, producing strong radio emission that can be spatially resolved, giving us a clear test for the jet hypothesis. Discussions are also given on what the jet would imply for the GRB-SN connection, when it is confirmed. We suggest the existence of two distinct classes of GRBs from similar core-collapse events but by completely different mechanisms. Cosmologically distant GRBs having an energy scale of $\sim 10^{50}$–10^{51} ergs are collimated jets generated by the central activity of core collapses, associated with ^{56}Ni ejection along with the jets. SN 2002ap can be considered as a failed GRB of this type with large baryon contamination. On the other hand, much less energetic ones including GRB 980425 are rather isotropic, which may be produced by hydrodynamical shock acceleration at the outer envelope. We propose that the radioactive ionization for the SN 2002ap jet may give a new explanation also for the X-ray line features often observed in GRB afterglows.

Subject headings: circumstellar matter — gamma rays: bursts — ISM: jets and outflows — polarization — supernovae: individual (SN 1998bw, SN 2002ap)

1. INTRODUCTION

Type Ic supernova (SN) 2002ap has attracted particular attention since its discovery by Y. Hirose in 2002 January because of its relatively close distance (about $D = 7.3$ Mpc; Sharina, Karachentsev, & Tikhonov 1996; Sohn & Davidge 1996) and its broad-line spectral features (Kinugasa et al. 2002) that are considered as a signature of very energetic supernovae. Such a supernova population, often called hypernovae, whose prototype is the famous Type Ic SN 1998bw, has an explosion energy more than 10 times larger than the standard energy ($\sim 10^{51}$ ergs) when spherical symmetry is assumed (Iwamoto et al. 1998; Woosley, Eastman, & Schmidt 1999; see also Höflich, Wheeler, & Wang 1999 for asymmetric modeling of these events with less extreme explosion energies). The apparent association of a gamma-ray burst (GRB) 980425 with SN 1998bw makes these mysterious events even more interesting in the context of the possible SN/GRB connection.[3] Mazzali et al. (2002) presented photometric and spectroscopic modeling of SN 2002ap assuming a spherical explosion and indicated that the explosion occurred at January 28 ± 0.5 UT, with a kinetic energy of about (4–10) $\times 10^{51}$ ergs, and the progenitor is a C + O star whose main-sequence mass is $\sim$20–25 $M_\odot$. It seems that an interacting binary is more likely for a star of this mass scale to lose its hydrogen and helium envelope, but theoretical and metallicity uncertainties do not reject a single Wolf-Rayet (W-R) star as another possible progenitor (Smartt et al. 2002).

In contrast to SN 1998bw/GRB 980425, SN 2002ap was not associated with a GRB to the sensitivity of IPN (Hurley et al. 2002; but see also Gal-Yam, Ofek, & Shemmer 2002). On the other hand, spectropolarimetric observations of SN 2002ap (Kawabata et al. 2002; Leonard et al. 2002; Wang et al. 2003) give an interesting hint for hidden energetic ejecta. Kawabata et al. (2002) noticed that the spectral shape of polarized continuum observed by Subaru around February 10 (i.e., $\sim$13 days after the explosion) apparently looks like the original unpolarized spectrum, but redshifted by $z = 0.3$ ($\lambda_{\rm redshifted}/\lambda = 1 + z$), and the ratio of the polarized to unpolarized flux is $f_P = 0.0018$ (in f_λ). The polarization angle (P.A.) is different from line polarization at this epoch or P.A. in their second observation in March (40 days after the explosion). Interestingly, they got a consistent P.A. and wavelength-independent polarization from February to March, which can be explained simply by an asymmetric photosphere as often seen in supernova spectra,

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[3] GRB 980425 was an exceptionally faint one compared with those found at cosmological distances. However, after the submission of this paper, SN 2003dh, a supernova having a similar spectrum to SN 1998bw, was discovered to be associated with the nearby GRB 030329 having normal luminosity (Stanek et al. 2003; Hjorth et al. 2003), finally confirming the connection between GRBs and energetic supernovae.

after they subtracted the redshifted polarized continuum in the February observation. If it is not a chance coincidence, this result can be explained by an asymmetric supernova photosphere *and* a jet moving at a much higher speed ($\sim cz \sim 0.3c$) than the supernova photosphere (Kawabata et al. 2002). Following this suggestion, Leonard et al. (2002) confirmed the resemblance between polarized and redshifted spectrum, by independent data taken by Keck, although statistical significance of this resemblance is difficult to assess.

As we show in § 2, jet mass of $M_{\rm jet} \sim 0.01\ M_\odot$ and jet kinetic energy of $E_{\rm jet} \sim 10^{50}$–10^{51} ergs are required to explain the degree of polarization. It is quite interesting in the perspective of the GRB-SN connection to note that the inferred jet energy is very close to the standard energy scale of collimated jets suggested for GRBs (Frail et al. 2001; Panaitescu & Kumar 2001). It is well known that an ultrarelativistic outflow with a Lorentz factor $\gamma \gtrsim 100$–1000 is required for successful GRBs to avoid the compactness problem (Goodman 1986; Paczyński 1986). It may be achieved by production of a fireball, where enormous energy is injected into a clean region with very low baryon contamination [$\sim 6 \times 10^{-6}(E/10^{51}\ {\rm ergs})(\gamma/100)^{-1}\ M_\odot$]. Then it is naturally expected that there may be events with similar jet energy but with much larger baryon contamination and hence low expansion velocity and no gamma-ray emission, often called "failed GRBs" or "dirty fireballs" (e.g., Huang, Dai, & Lu 2002). The energetic jet inferred for SN 2002ap may be the first detection of a failed GRB. On the other hand, even successful GRBs may also have jets with low velocity and high baryon load, which are produced in the process of jet acceleration in addition to the ultrarelativistic component responsible for GRBs. SN 2002ap may have been a successful GRB, but the jet was not directed to us.

However, this jet hypothesis has been questioned at a few points. Radio emission is thought of as an indicator for the existence of fast moving ejecta, since it would produce nonthermal synchrotron emission by interaction with circumstellar matter (CSM) or interstellar matter (ISM). However, radio emission of SN 2002ap is much (by more than 3 orders of magnitude) weaker than that of SN 1998bw, and Berger, Kulkarni, & Chevalier (2002, hereafter BKC02) have shown that the observed radio emission can be explained by synchrotron radiation produced by spherical ejecta expanding at $\sim 0.3c$ with a total energy of nonthermal electrons of $E_e \sim 1.5 \times 10^{45}$ ergs, assuming energy equipartition between electrons and magnetic fields. These numbers should be compared with those for SN 1998bw, i.e., relativistic shock speed with a Lorentz factor $\gamma \sim$ few and $E_e \sim 10^{49}$ ergs (Kulkarni et al. 1998). Based on this result, BKC02 argued that the energetic jet with $E_{\rm jet} \sim 10^{51}$ ergs proposed by Kawabata et al. (2002) should have produced much stronger radio emission than observed. Wang et al. (2003) presented VLT spectropolarimetric observations including earlier epochs than Keck and Subaru and found that the continuum polarization evolved from nearly zero on February 3 to 0.2% on February 10, which is contrary to what is expected from a simple jet model, since scattering efficiency should be higher in earlier epochs when jet location is closer to the star. Finally, it is uncertain whether the jet material is kept highly ionized in spite of the expected rapid adiabatic cooling.

The main purpose of this work is to examine whether the jet hypothesis is physically tenable, especially against the possible difficulties mentioned above. We found that it is in fact physically possible that the jet exists but has been spirited away from intensive observational efforts made so far, except for the Subaru spectropolarimetry. However, it is still a hypothesis, and we need a further observational test to prove this. Fortunately, we show that there is a good test for this hypothesis by future observation; we point out that a long-term radio monitoring of this object should find reemergence of radio emission in a few to 10 yr, for which the jet expansion should be easily resolved by VLBI imaging. Then, we give discussions on what would be the implications for the GRB-SN connection if the jet is confirmed in the future. Here we also propose a new possible explanation for X-ray line features often observed in GRB afterglows, which is inspired by the results of the paper.

The paper is organized as follows. We give an estimate of the jet mass and energy with a fully relativistic treatment in § 2. We discuss the physical condition of the jet including ionization sources in § 3 and give a detailed modeling of radio emission from the interaction between the jet and CSM/ISM in § 4. In § 5 we discuss the GRB-SN connection and X-ray lines in GRB afterglows, and a summary and conclusions are presented in § 6.

2. JET MASS AND ENERGY ESTIMATION

We assume that the jet is sufficiently collimated and hence we can define a single scattering angle of photons scattered by the jet, $\theta_{\rm obs}$, which is the same as the direction angle of the observer measured from the jet direction. We also assume that the jet is optically thin for the electron scattering, which will be checked later. If the jet is optically thin, the jet mass and energy estimates in this section do not depend on the jet opening angle. We use a notation that x and x' are the quantities in the rest frames of the supernova/observer and the jet, respectively. (The heliocentric redshift of the host galaxy is $+631$ km s^{-1} [Smartt & Meikle 2002] and can be neglected.) According to the standard Lorentz transformation, the energy of original photons from the supernova has a relation

$$\epsilon'_{\rm org} = \gamma(1-\beta)\epsilon_{\rm org}\ , \qquad (1)$$

and for the energy of scattered photons by the jet,

$$\epsilon'_{\rm sc} = \gamma(1-\beta\cos\theta_{\rm obs})\epsilon_{\rm sc}\ , \qquad (2)$$

where β and γ are the bulk velocity and Lorentz factor of the jet, respectively. From these relations and using $\epsilon'_{\rm org} = \epsilon'_{\rm sc}$ for the Thomson scattering, we have the relation between the original and scattered photon energies:

$$\frac{\epsilon_{\rm sc}}{\epsilon_{\rm org}} = \frac{1}{1+z} = \frac{1-\beta}{1-\beta\cos\theta_{\rm obs}}\ . \qquad (3)$$

The inverse Lorentz transformation of equation (2) leads to

$$\epsilon_{\rm sc} = \gamma(1+\beta\cos\theta'_{\rm obs})\epsilon'_{\rm sc}\ , \qquad (4)$$

and hence $\theta_{\rm obs}$ and $\theta'_{\rm obs}$ are related as

$$\gamma^2(1-\beta\cos\theta_{\rm obs})(1+\beta\cos\theta'_{\rm obs}) = 1\ . \qquad (5)$$

We should consider three timescales: the time when we observe a scattered photon ($t_{\rm obs}$, measured from the arrival time of unscattered photons emitted at the core-collapse date), that when the photon is scattered by the jet ($t_{\rm sc}$), and that when the photon is originally radiated from the supernova photosphere ($t_{\rm rad}$). The last two are measured from the core-collapse date in the supernova/observer rest frame. From a geometrical calculation, we find

$$t_{\rm sc} = \frac{1}{1-\beta\cos\theta_{\rm obs}} t_{\rm obs} \ , \qquad (6)$$

$$t_{\rm rad} = \frac{1-\beta}{1-\beta\cos\theta_{\rm obs}} t_{\rm obs} = \frac{1}{1+z} t_{\rm obs} \ . \qquad (7)$$

Let $F_{\rm org}(t_{\rm sc}) = L_{\rm org}(t_{\rm rad})/(4\pi r_{\rm jet}^2)$ be the original flux from the supernova at the jet location, $r_{\rm jet} = c\beta t_{\rm sc}$, and the flux in the jet rest frame is

$$F'_{\rm org} = \gamma^2(1-\beta)^2 F_{\rm org} \ . \qquad (8)$$

The luminosity of scattered light per unit solid angle is given as

$$\frac{dL'_{\rm sc}(\theta'_{\rm obs})}{d\Omega} = N_e \frac{d\sigma(\theta'_{\rm obs})}{d\Omega} F'_{\rm org} \ , \qquad (9)$$

where $N_e = M_{\rm jet} f_{\rm el}/(\mu_e m_p)$ is the free electron number in the jet, μ_e is the nucleon-to-electron number ratio, m_p is the proton mass, and $f_{\rm el}$ is the fraction of free ionized electrons. Assuming that the jet material is mostly heavy element, e.g., C + O, we set $\mu_e = 2$. Here

$$d\sigma(\theta'_{\rm obs})/d\Omega = (3/16\pi)\sigma_{\rm T}(1+\cos^2\theta'_{\rm obs})$$

is the cross section of Thomson scattering for unpolarized light. The scattered luminosity $dL'_{\rm sc}/d\Omega$ is related to that in the supernova/observer rest frame as (e.g., Rybicki & Lightman 1979)

$$\frac{dL_{\rm sc}(\theta_{\rm obs})}{d\Omega} = \frac{1}{\gamma^4(1-\beta\cos\theta_{\rm obs})^4} \frac{dL'_{\rm sc}(\theta'_{\rm obs})}{d\Omega} \ . \qquad (10)$$

The ratio of polarized to unpolarized flux, f_P, is given as

$$f_P(\theta_{\rm obs}) = \Pi(\theta'_{\rm obs}) \frac{dL_{\rm sc}}{d\Omega} \left[\frac{L_{\rm org}(t_{\rm obs})}{4\pi}\right]^{-1} \frac{1}{1+z} \ , \qquad (11)$$

where $\Pi = (1-\cos^2\theta'_{\rm obs})/(1+\cos^2\theta'_{\rm obs})$ is the degree of polarization of the scattered wave and the last factor of $(1+z)^{-1}$ is coming from the definition of f_P by the ratio of flux per unit wavelength, f_λ.

From equations (6) and (7), the fractional time delay of scattered photons from direct unscattered photons is $(t_{\rm obs} - t_{\rm rad})/t_{\rm obs} = 1-(1+z)^{-1} = 0.23$, which is small and independent of unknown $\theta_{\rm obs}$. Since the luminosity and spectrum of the supernova are not expected to change significantly within these timescales, we expect that the scattered spectrum is similar to the unscattered one except for the redshift, as observed. Therefore, we do not have to take into account the luminosity and spectral evolution of the supernova, i.e., $t_{\rm rad} \sim t_{\rm obs}$. In the top and middle panels of Figure 1 we show β, γ, $M_{\rm jet}$, and $E_{\rm jet} = M_{\rm jet}c^2(\gamma-1)$ required to reproduce the observed redshift ($z = 0.3$) and degree of polarization ($f_P = 1.8 \times 10^{-3}$), as a function of the jet viewing angle, $\theta_{\rm obs}$. Here we have assumed $f_{\rm el} = 0.3$ and $t_{\rm obs} = 10$ days, and scaling of the results by different values of these parameters is obvious.

It is likely that there is another jet in the opposite direction from the supernova, in addition to the jet considered so far, and the opposite jet should also produce another redshifted polarization component. Since the data show only one redshifted component, the contribution from this opposite jet must be with similar polarization degree and redshift to the original jet or negligibly small as a result of too small f_P or very large redshift. In the bottom panel of Figure 1 we plot the redshift ($z_{\rm op}$) and the polarization degree ($f_{P,{\rm op}}$) by the opposite jet having the same jet velocity and mass but $\theta_{\rm obs,op} = 180° - \theta_{\rm obs}$. This gives a constraint of $\theta_{\rm obs} \lesssim 100°$; otherwise, we should have observed another polarized continuum component with larger f_P and smaller redshift than the observed ones.

The jet velocity is roughly constant at $\beta \sim 0.2$ for $\theta_{\rm obs} \gtrsim 90°$, but it becomes more relativistic with decreasing $\theta_{\rm obs}$ at $\theta_{\rm obs} \lesssim 90°$ because the redshift effect of the jet motion is compensated by the blueshift to the observer. The jet mass and energy rapidly become larger with decreasing $\theta_{\rm obs}$, mainly because of less efficient polarization and larger $r_{\rm jet} \propto t_{\rm sc} \gg t_{\rm obs}$. Small $\theta_{\rm obs}(\lesssim 60°)$ seems not favored from energetics, since it requires jet energy of more than 10^{52} ergs.

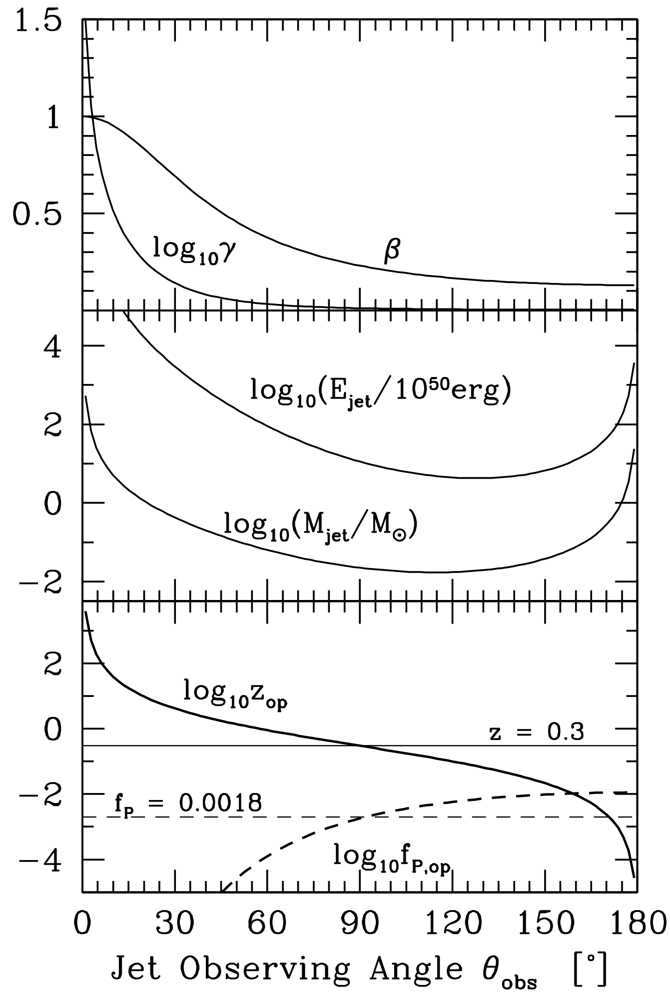

FIG. 1.—*Top and middle panels*: Jet velocity β, Lorentz factor γ, the jet mass $M_{\rm jet}$, and the jet kinetic energy $E_{\rm jet}$ required to explain the observed redshift ($z = 0.3$) and polarization degree ($f_P = 1.8 \times 10^{-3}$), as a function of the observer's direction $\theta_{\rm obs}$ measured from the jet direction. *Bottom panel*: Polarization degree ($f_{P,{\rm op}}$) and redshift ($z_{\rm op}$) expected for the opposite jet having the direction of ($180° - \theta_{\rm obs}$), with the same jet parameters shown in the top and middle panels. Observed redshift and f_P are marked by horizontal lines.

These considerations lead to a conclusion that the jet directions must be close to $\theta_{\rm obs} \sim 90°$ (probably within $\pm10°$–$20°$) and both the two jets contributed roughly equally to the observed polarization. Therefore, we assume two jets with $\theta_{\rm obs} = 90°$ in this work. Then we found $\beta = 1 - (1+z)^{-1} = 0.23$, and the jet mass is

$$M_{\rm jet} = 0.011 \left(\frac{f_P}{0.0018}\right)\left(\frac{t_{\rm obs}}{10\ {\rm days}}\right)^2 \left(\frac{f_{\rm el}}{0.3}\right)^{-1} M_\odot\ , \quad (12)$$

where $M_{\rm jet}$ is redefined as the mass of each jet. Therefore, observed redshifted polarization can be explained if the jet material is modestly ionized, with the kinetic jet energy $E_{\rm jet} \sim 5 \times 10^{50} (M_{\rm jet}/0.01\ M_\odot)(\beta/0.23)^2$ ergs. In the following sections we consistently use $\theta_{\rm obs} = 90°$, $t_{\rm sc} = t_{\rm obs}$, $\beta = 0.23$, and $M_{\rm jet} = 0.01\ M_\odot$.

3. PHYSICAL CONDITIONS OF THE JET AND IONIZATION

3.1. *Jet Is Freely Expanding*

First we consider the fact that the radio emission from SN 2002ap was very weak. If a considerable part of the jet kinetic energy was converted into nonthermal electrons via shock acceleration, inevitably there must be very strong radio emission that should have been even stronger than SN 1998bw. However, if the amount of CSM swept up by the jet is much smaller than the jet mass, the jet feels almost no deceleration and the majority of the jet material remains unshocked. We do not expect radio emission from such an almost freely expanding jet, and we only expect radio emission by CSM swept up by the jet. This emission and the total energy of radio-emitting electrons ($\sim 10^{45}$ ergs) are simply related by the jet velocity and CSM density and *not* related with the total jet mass and kinetic energy. The stellar wind mass-loss rate of W-R stars, which are considered as a possible candidate of the SN Ic progenitors, is typically $\dot{M}_w \sim 10^{-6}$ to $10^{-5}\ M_\odot\ {\rm yr}^{-1}$ with a wind velocity of $V_w \sim 10^3\ {\rm km\ s}^{-1}$ (McCray 1983; García-Segura, Langer, & Mac Low 1996a; García-Segura, Mac Low, & Langer 1996b). It is generally assumed that the CSM around radio supernovae has a stellar wind profile, i.e., $\rho_{\rm CSM}(r) = \dot{M}_w/(4\pi r^2 V_w)$. Then the swept-up mass by the jet becomes

$$M_{\rm sw} = b\dot{M}_w r_{\rm jet}/V_w = 1.9 \times 10^{-7} b_{-1} \dot{M}_{w,-6} V_{w,3}^{-1} t_{10}\ M_\odot\ ,$$

where $b = 0.1 b_{-1} = \Omega_{\rm jet}/4\pi$ is the beaming factor of the jet opening angle, $t_{10} = t_{\rm obs}/10$ days,

$$\dot{M}_{w,-6} = \dot{M}_w/(10^{-6}\ M_\odot\ {\rm yr}^{-1})\ , \quad V_{w,3} = V_w/(10^3\ {\rm km\ s}^{-1})\ .$$

This is much smaller than the jet mass and hence the jet is not decelerated.

Radio emission from SN 1998bw and SN 2002ap can be explained by isotropic high-speed ejecta interacting with the CSM density consistent with the wind parameters similar to the above values (Kulkarni et al. 1998; Li & Chevalier 1999; BKC02). (The speed of ejecta is, however, considerably different for these two: $\gamma_{\rm ej} \sim$ few for the former but $v_{\rm ej} \sim 0.3c$ for the latter.) Since the inferred jet velocity of SN 2002ap is close to $v_{\rm ej}$ and the swept-up CSM mass by the jet should be smaller than that by isotropic ejecta because of the collimation, it looks reasonable that the radio emission from the external shock front of the jet is equal to or smaller than the observed radio emission. We present more detailed radio emission modeling in § 4.

Therefore, the weak radio flux from SN 2002ap does not immediately exclude the jet hypothesis, if it is expanding freely. It may also be useful to recall that the kinetic energy of supernovae ($\sim 10^{51}$ ergs) is hardly converted into radiation, but supernovae are heated and shining by radioactivity. However, free expansion raises another problem because of the expected rapid adiabatic cooling. The jet material must be ionized at least modestly, but as we show below, the adiabatic cooling is so strong that the temperature of the jet material is likely lower than that necessary to keep it ionized. Therefore, we need an external radiation or heating source of ionization. We discuss this issue in detail below.

3.2. *Optical Depth and Thinning Burst*

First, we check the optical depth of the jet material to the photon-electron scattering. The jet must be mostly transparent to radiation at day ~ 13 for the jet material to contribute the scattering and polarization efficiently. It can be written as

$$\tau_{\rm jet} \sim \frac{f_{\rm el} M_{\rm jet}}{\mu_e m_p} \frac{\sigma_{\rm T}}{4\pi b r_{\rm jet}^2} = 0.088 f_{\rm el} b_{-1}^{-1} t_{10}^{-2}\ . \quad (13)$$

Therefore, the jet becomes optically thin at a time $t_{\rm th} \sim 3.0 f_{\rm el}^{1/2} b_{-1}^{-1/2}$ days. This thinning time is close to the epoch when the continuum polarization evolved from nearly zero to the 0.2% level in the VLT observation, hence indicating that the initially unobserved polarization can be explained by high optical depth of the jet.

In analogy to the fireball theory for GRBs, we expect a burst of radiation when the jet becomes optically thin (Mészáros, Laguna, & Rees 1993), and here we examine how much radiation we expect from this. Suppose that the jet is in thermal equilibrium and the total internal energy is comparable with the kinetic energy of the jet, $E_{\rm jet}$, at the initial radius r_i. If the jet interacts with the stellar envelope and dissipate its kinetic energy, the radius of the progenitor C + O star, $r_i \sim 10^{10}$ cm, is a reasonable choice, while another possibility is $r_i \sim 10^6$ cm if the jet is directly emitted from the central compact neutron star or black hole. The initial temperature T_i is determined by the internal energy density $U_i = E_{\rm jet}/V_i$, and both the internal energy and temperature adiabatically decrease as $\propto (r_{\rm jet}/r_i)^{-1}$, where $V_i = 4\pi\zeta r_i^3$ is the initial volume of the jet material and ζ is the fractional thickness of the jet shell. Here we assumed that the jet is homologously expanding like supernova ejecta, and hence $V \propto r_{\rm jet}^3$. Then we find the internal energy and temperature at the thinning time $t_{\rm th}$ as

$$E_{\rm th} \sim 2.8 \times 10^{45} f_{\rm el}^{-1/2} b_{-1}^{1/2} r_{i,10}\ {\rm ergs}\ , \quad (14)$$

$$k_{\rm B} T_{\rm th} \sim 0.41 f_{\rm el}^{-1/2} b_{-1}^{1/4} \zeta_{-1}^{-1/4} r_{i,10}^{1/4}\ {\rm eV}\ , \quad (15)$$

where $\zeta_{-1} = \zeta/0.1$ and $r_{i,10} = r_i/(10^{10}\ {\rm cm})$. The flux of this thinning radiation is

$$F_{\rm th} \sim E_{\rm th}/(4\pi D^2 t_{\rm th}) = 1.7 \times 10^{-12} f_{\rm el}^{-1} b_{-1} r_{i,10}\ {\rm ergs\ cm^{-2}\ s^{-1}}\ ,$$

which is sufficiently smaller than the observed UV–

optical–IR flux of $\sim 2 \times 10^{-10}$ ergs cm^{-2} s^{-1} at day 5 (Sutaria et al. 2003).

If there is no external heating or ionizing radiation source, the ionization balance of the jet would be determined by collisional ionization coefficient $q_{\rm col}$ by thermal electrons and radiative recombination coefficient $\alpha_{\rm rec}$. Comparing coefficients of these processes (Lotz 1967; Nahar & Pradhan 1997; Nahar 1999), the temperature must be higher than $\sim$5 eV for the C + O matter to be ionized doubly or more. Considering the temperature derived above and the weak dependence on the unknown parameters, it seems unlikely that the jet is sufficiently hot to keep itself ionized. After the jet becomes optically thin, radiative cooling may further decrease the temperature. Then we need an external source of heating or ionizing photons.

3.3. *Photoionization*

To begin with, we estimate the total ionizing photon luminosity required to keep all the jet material ionized (a similar argument used to derive the Strömgren radius). This is given by the recombination rate as

$$L_{\rm ph,rec} \sim \alpha_{\rm rec} n_e N_{\rm ion} = 5.6 \times 10^{50} b_{-1}^{-1} \zeta_{-1}^{-1} \mu_{14}^{-1} t_{10}^{-3} \times \left(\frac{\alpha_{\rm rec}}{10^{-11}\ {\rm cm}^3\ {\rm s}^{-1}}\right)^{-1} \left(\frac{f_{\rm el}}{0.3}\right) {\rm s}^{-1} , \quad (16)$$

where n_e is the free electron number density, $N_{\rm ion}$ is the number of ions, and $\mu_{\rm ion} = 14\mu_{14}$ is the mean molecular weight of ions. Correspondingly, the ionizing flux in the jet must be stronger than $F_{\rm ion} \sim L_{\rm ph,rec}/(4\pi b r_{\rm jet}^2)$, and the abundance ratio between species $X^{+i+1} + e^- \leftrightarrow X^i$ is given as

$$\frac{N(X^{+i+1})}{N(X^i)} = \frac{\sigma_{\rm ion} F_{\rm ion}}{\alpha_{\rm rec} n_e} \quad (17)$$

$$= 9.4 \times 10^4 b_{-1}^{-1} \mu_{14}^{-1} t_{10}^{-2} \left(\frac{\sigma_{\rm ion}}{5 \times 10^{-18}\ {\rm cm}^2}\right) . \quad (18)$$

Here we used typical values of $\alpha_{\rm rec}$ and ionization cross section $\sigma_{\rm ion}$ for $C^+ \leftrightarrow C^{+2}$ or $O^+ \leftrightarrow O^{+2}$ at temperature $\sim$1 eV (Osterbrock 1989). Therefore, a necessary and sufficient condition for ionization is that the jet matter is radiated with a total photon luminosity given in equation (16).

First, we consider the possibility of ionization by radiation from the supernova. The effective temperature inferred from optical colors of SN 2002ap at day $\sim$10 is about $T_{\rm eff} \sim 6000$ K (Gal-Yam et al. 2002), and the number of photons in the blackbody tail above $\nu_T \sim 6 \times 10^{15}$ GHz, which is a threshold frequency of ionizing photons for C II and O II, is quite small.

There is an *XMM-Newton* observation of SN 2002ap on February 2 UT, i.e., about 5 days after the explosion (Soria & Kong 2002; Sutaria et al. 2003). The flux in 0.3–10 keV is 1.07×10^{-14} ergs cm^{-2} s^{-1}, and the spectrum can be fitted with a power law with a photon index of $\alpha_{\rm X} = 2.6^{+0.6}_{-0.5}$ ($f_\nu \propto \nu^{-\alpha_{\rm X}+1}$). The flux extrapolated down to UV bands may ionize the jet, and softer spectrum gives stronger ionization flux.

However, the following arguments give further constraints on the possible range of $\alpha_{\rm X}$. Sutaria et al. (2003) ascribed this X-ray flux to be inverse Compton scattering of the optical photons, and in this case the extrapolated nonthermal flux down to the optical bands should be about $\tau_{\rm CSM} F_{\rm opt}$, where $\tau_{\rm CSM}$ is the optical depth of hot electrons in shocked CSM around the supernova and $F_{\rm opt}$ is the optical flux of the supernova (Fransson 1982; Chevalier & Fransson 2001; Sutaria et al. 2003). The hot CSM gas responsible for X-ray emission is swept up by either the jet or other isotropic fast ejecta as considered by BKC02 (see also § 4 for examination of these two possibilities from radio data). In either case, the velocity of the shock front is 0.23c–0.3c, and hence the location of the X-ray–emitting region is $r_{\rm X} \sim 6.0 \times 10^{15} t_{10}$ cm. Therefore, we find

$$\tau_{\rm CSM} = 2.0 \times 10^{-5} \dot{M}_{w,-6} V_{w,3}^{-1} t_{10}^{-1} b_{\rm X} ,$$

where $b_{\rm X}$ is the sky coverage of the X-ray–emitting region viewed from the supernova photosphere; $b_{\rm X} = 1$ for the isotropic ejecta while $b_{\rm X} = b$ for the jet. As we show in § 4, $\dot{M}_w \lesssim 10^{-4}\ M_\odot$ yr^{-1} is required for successful modeling of the observed radio data. Then, comparing with the observed optical flux, $\alpha_{\rm X} \lesssim 2.6$ and 2.2 is required for $b_{\rm X} = 1$ and $b_{\rm X} = b = 0.1$, respectively, even though softer index is allowed by the observational error. BKC02, on the other hand, suggested that the X-ray flux is explained by the same synchrotron radiation as the radio observations. The radio and X-ray fluxes at day 5 are connected by a power law with a photon index of $\alpha'_{\rm X} = 1.5$, and considering that the photon index changes by 0.5 below and above the cooling break frequency, the maximum photon index allowed in the X-ray band is $\alpha_{\rm X} < \alpha'_{\rm X} + 0.5 = 2$, irrespective of $b_{\rm X}$.

Now we compare these constraints on $\alpha_{\rm X}$ with the range required to ionize the jet. The observed X-ray flux at day 5 should not be much different at day $\sim$10–13, and we extrapolate the X-ray luminosity down to the UV band and compare to $L_{\rm ph,rec}$. Note that only a fraction of the X-ray luminosity is directed to the jet material, and this fraction is given by $\sim b/b_{\rm X}$ from a geometrical consideration. We found that the spectral index must be extremely soft as $\alpha_{\rm X} \gtrsim 5$ or 4 for $b_{\rm X} = 1$ or $b_{\rm X} = b = 0.1$, respectively, in order that the extrapolated flux down to ν_T is equal to $L_{\rm ph,rec}$. Therefore, we can safely exclude the possibility that the nonthermal radiation producing the observed X-rays is ionizing the jet.

Second, we consider a possibility that a hot, UV-radiating star close to SN 2002ap may ionize the jet. It is expected that SN 2002ap occurred in a massive star-forming region where young massive stars are clustering. A close binary system is a candidate for the Type Ic supernova progenitors (Nomoto, Filippenko, & Shigeyama 1990), and it may provide an even stronger ionization source. However, the total ionization luminosity given in equation (16) is even larger by a factor of several than the ionization flux, $\sim 10^{49.5}$ s^{-1}, above the frequency $\nu_T \sim 6 \times 10^{15}$ Hz for the most luminous and hottest stars (Schaere & de Koter 1997). It should be noted that this luminosity is for all directions, but only the radiation within the solid angle of the jet viewed from the ionizing star is available for the jet ionization, which is expected to be a small fraction. If the region around SN 2002ap is filled up by the radiation field with $\sim F_{\rm ion}$ to a radius of $r_{\rm jet}$, the region should have a luminosity of at least $4\pi F_{\rm ion} r_{\rm jet}^2$, corresponding to a bolometric luminosity of

$$2.1 \times 10^8 b_{-1}^{-2} \zeta_{-1}^{-1} \mu_{14}^{-1} t_{10}^{-3} (f_{\rm el}/0.3)\ L_\odot ,$$

assuming the spectral energy distribution of the most luminous O stars. Such a huge luminosity is apparently ruled out by the prediscovery image of the SN 2002ap field reported by Smartt et al. (2002). To conclude, ionization by nearby young stars is impossible.

3.4. *Radioactive Heating and Collisional Ionization*

Since photoionization of the jet seems difficult, the only way to ionize the jet is enhanced collisional ionization by external heating. If the jet is generated at the central compact object, it might include a significant amount of radioactive nuclei such as ^{56}Ni. Asymmetric explosion induced by the jet should also affect nucleosynthesis, and ^{56}Ni production along the jet direction is enhanced (Nagataki 2000; Maeda et al. 2002). ^{56}Ni decays by electron capture and gamma-ray emission to ^{56}Co, with an exponential decay timescale of $t_{\rm Ni} = t_{1/2}/\ln(2) = 8.5$ days and a decay energy of $\epsilon_{\rm Ni} = 2.1$ MeV. When the material is optically thick, the radioactive heat is quickly thermalized into an optical radiation field, as generally seen for supernovae. On the other hand, if the material is mildly optically thin, the gamma rays emitted by decaying ^{56}Ni scatter electrons with a probability $\sim\tau_{\rm jet}$, and since the gamma-ray energy is comparable with the electron rest mass, the scattered electrons acquire mildly relativistic speed and energy. Such high-energy electrons would lose their energy by ionization loss in the jet plasma, with a timescale of

$$t_{\rm il} \sim 2.0 \times 10^4 (v_e/c)^4 t_{10}^3 \zeta_{-1} b_{-1} \text{ s} , \tag{19}$$

where v_e is the initial velocity of high-energy electrons. Here we used the ionization loss formulae of Longair (1992) and the logarithmic factor is set to be 15. Therefore, the energy deposited by radioactive gamma rays is used to ionize the jet material within the timescale of interest, giving an efficient ionization process. When optical depth is very low, this process would be dominated by positrons emitted from the decay of ^{56}Co, which has a longer exponential lifetime of $t_{\rm Co} = 111.26$ days, and the energy fraction given to positrons is 3.5% of the total decay energy (Arnett 1979; Woosley, Pinto, & Hartmann 1989).

The ionizing balance is determined by the energy balance between radioactive heating and recombination cooling (see also Graham 1988) as

$$\tau_{\rm jet} \frac{f_{\rm Ni} M_{\rm jet}}{\mu_{\rm Ni} m_p} \epsilon_{\rm Ni} \frac{\exp(-t_{\rm sc}/t_{\rm Ni})}{t_{\rm Ni}} \gtrsim \alpha_{\rm rec} n_e N_{\rm ion} w , \tag{20}$$

where $f_{\rm Ni}$ is the ^{56}Ni mass fraction in the jet and w is the ionization potential. The recombination rate coefficient depends on the electron gas temperature, which is determined by balance between the radioactive heating and cooling processes. We can estimate the minimum amount of ^{56}Ni by taking the minimum value of $\alpha_{\rm rec}$ as

$$f_{\rm Ni} \gtrsim 0.68 t_{10}^{-1} \zeta_{-1}^{-1} e^{(t-10 \text{ days})/t_{\rm Ni}} \mu_{14}^{-1} w_{20} \left(\frac{\alpha_{\rm rec}}{3 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}} \right) , \tag{21}$$

where the adopted value of $\alpha_{\rm rec}$ is the minimum value of doubly ionized oxygen or carbon at a temperature of $\sim 10^4$ K (Nahar & Pradhan 1997; Nahar 1999) and $w_{20} = w/(20 \text{ eV})$. The jet may include a significant amount of heavier nuclei that are difficult to ionize for a fixed value of $f_{\rm el}$, but on the other hand, it may also include considerable helium that is easier to ionize. The helium could be mixed from the remaining helium layer of the progenitor, or it may be newly synthesized. Production of helium is also enhanced along the jet direction in energetic jetlike nucleosynthesis (Maeda et al. 2002). We also note that highly ionized heavy nuclei, such as ^{56}Ni, should produce observable line emission in X-ray bands, and hence the observed weak X-ray flux gives a constraint on the species of ionized elements. (See § 5.2 for a possible connection to X-ray line features often observed in GRB afterglows.) Whatever the jet composition is, the above result indicates that, if the jet is kept ionized by radioactive heating, it must have a considerable amount of ^{56}Ni (mass fraction of order unity). This estimate is, however, very uncertain, especially about the composition of the jet, $\alpha_{\rm rec}$, and electron temperature. More sophisticated treatment is necessary to determine the ionization status, but it is beyond the scope of the paper. Therefore, it is difficult to conclude that the jet should be ionized, but it seems to be the best candidate of ionization process among others.

The jet may be ionized by gamma rays of ^{56}Ni decay leaking from the photosphere of SN 2002ap, even if the jet does not have radioactive nuclei. In fact, ionization of the helium envelope above the photosphere, which is required to explain the observed He lines in SN 1987A and Type Ib supernovae, is ascribed to the leaking gamma rays from the photosphere (Graham 1988; Lucy 1991). The mass of ^{56}Ni produced by SN 2002ap is estimated to be $0.07 \pm 0.02\ M_\odot$ from the light-curve modeling by Mazzali et al. (2002), which is larger than the jet mass. However, the efficiency for gamma rays to hit the jet is reduced by the beaming factor, b, and it is further reduced by the escaping fraction from the photosphere. Although some supernovae, including SN 1998bw, showed evidence that a significant amount of gamma rays are leaking in late phase ($\gtrsim 30$ days; Nakamura et al. 2001; Patat et al. 2001), the leaking fraction should not be large in early phase of ~ 10 days, when the optical luminosity is still glowing up by diffusion of radioactive heat to the photosphere. According to the model of Mazzali et al. (2002), about 10% of gamma rays are leaking, most of which are produced by ^{56}Ni outside the photosphere, at day ~ 10 (K. Maeda & K. Nomoto 2003, private communication). This should be considered as an upper limit for the leaking fraction since the model assumes the maximally possible mixing, i.e., uniform distribution of ^{56}Ni. (The best-fit model of Mazzali et al. 2002 has less significant mixing.)

Therefore, leaking gamma rays from or around the photosphere seem less efficient than ^{56}Ni in the jet, if the ^{56}Ni distribution is what is expected from isotropic modeling. However, if the explosion is very asymmetric as a result of the jet formation activity and considerable amount of ^{56}Ni is ejected outside the photosphere, it may ionize the jet. It should also be noted that SN 1998bw produced much larger amounts of ^{56}Ni ($\sim 0.7\ M_\odot$; Iwamoto et al. 1998) than SN 2002ap. We cannot reject that a comparable ^{56}Ni was produced also in SN 2002ap, but most of it is well outside the photosphere where optical depth is low and radioactive decay energy mostly escapes as gamma rays, not in optical bands. Such ^{56}Ni could be missed in the modeling by Mazzali et al. (2002) based on optical observations. Such extreme mixing and distribution of ^{56}Ni is unlikely to occur simply by hydrodynamical instability in C + O stars (K. Maeda & K. Nomoto 2003, private communication; see also Shigeyama et al. 1990). Hence, significant ejection of ^{56}Ni from the stellar core by jet formation activity is again indicated.

4. RADIO EMISSION BY SWEPT-UP MATERIAL

4.1. *Early Emission by Interaction with Presupernova Wind*

The observed radio emission is considered to be produced by shocked CSM swept up by high-velocity supernova ejecta. There are two possibilities: (1) the observed radio flux is generated by CSM swept up by the jet responsible for the redshifted polarization; or (2) the radio flux is from CSM swept up by isotropic supernova ejecta that is a different component from the jet, as considered by BKC02, and the radio emission by CSM swept up by the jet was weaker than observed. The former option predicts that the shock front of the radio emission region is not decelerating; otherwise, the shock generated in the jet material would overproduce much the observed radio flux. On the other hand, since the expansion velocity of the isotropic shell considered by BKC02 is similar to that of the jet, the mass of the isotropic ejecta in the latter option must be much smaller than the jet mass; otherwise, the isotropic component would spoil the redshifted polarization produced by scattering in the jet. The mass of the isotropic component can be as small as the swept-up CSM, which is much smaller than the jet mass as argued above, and it should be decelerated by swept-up CSM. BKC02 found that the radio data are not sufficient to constrain whether the shock radius is decelerating or not and hence cannot constrain this possibility. Here we examine possibility 1 by a detailed modeling of the observed radio emission with a collimated jet.

Given the jet opening angle and the density of CSM (determined by $\dot{M}_w$ and V_w), we can calculate the mass and energy density of shocked CSM swept up by the jet moving at a constant velocity, $0.23c$. We assumed the strong shock limit with a compression factor of 4, and the temperature of the shocked CSM is calculated by the standard shock theory for supersonic piston. Then we can calculate the synchrotron flux according to the standard formulae, if fractional energy densities of nonthermal electrons (ϵ_e) and magnetic field (ϵ_B), electron power index (p, $dN_e/d\gamma_e \propto \gamma_e^{-p}$), and the minimum Lorentz factor of nonthermal electrons (γ_m) are specified. We calculated the synchrotron flux taking into account synchrotron self-absorption (SSA) by formulations given in Li & Chevalier (1999) and also free-free absorption (FFA) by formulations in Weiler et al. (1986), assuming preshocked CSM temperature $T_{\rm CSM} = 10^4$ K. We fix $\epsilon_e = 0.05$ and find best-fit parameters of $\dot{M}_w$ and ϵ_B to the observed radio data (BKC02) by χ^2 analysis, as a function of the beaming factor b. The radio flux is showing evidence of modulation, presumably due to the interstellar scattering and scintillation (ISS), and the minimum χ^2 is unacceptably large without this effect taken into account. Here we calculate the ISS modulation index with parameters given in BKC02, and it is added to the observational flux errors as a quadratic sum. The wind velocity is fixed to $V_w = 10^3$ km s^{-1}, and different values of V_w simply rescale $\dot{M}_w$ via the CSM density ($\propto \dot{M}_w/V_w$). The change of ϵ_e is also mostly canceled by scaling of $\dot{M}_w$, except for the strength of the free-free absorption. We checked that changing ϵ_e by 1 order of magnitude does not affect conclusions derived below. The magnetic field strength can be expressed as $B = 0.21 \dot{M}_{w,-6}^{1/2} V_{w,3}^{-1/2} (\epsilon_B/0.01)^{1/2}$ G.

The best-fit $\dot{M}_w$ and ϵ_B, as well as the χ^2 value, are given in Figure 2. Here we used two extreme values of γ_m: a low value $\gamma_{m,l} = \gamma$ and a high value $\gamma_{m,h} = 1 + \mu_e m_p(\gamma - 1)/m_e$ for the thick and thin lines, respectively. The former corresponds to a case in which the electron minimum energy simply reflects the velocity of the shock, while the latter corresponds to a case in which the kinetic energy of ions is efficiently transferred to electrons. We also used three values of $p = 2.2$, 2.5, and 2.8. The characteristic synchrotron frequency (ν_m) corresponding to γ_m, the SSA frequency ($\nu_{\rm SSA}$), and the FFA frequency ($\nu_{\rm FFA}$) at day 7 in these results are given in Figure 3, but only for the $p = 2.2$ case. The χ^2 degree of freedom is $n_{\rm dof} = 24 - 3 = 21$, and the minimum reduced $\tilde{\chi}^2 \equiv \chi^2/n_{\rm dof}$ is less than unity, i.e., an acceptable fit. The confidence limit projected on parameter b can be estimated by a region where $\Delta\chi^2$, i.e., the difference of χ^2 from the minimum, is smaller than a certain value; $\Delta\tilde{\chi}^2 < 0.19$ and 0.32 for 95.4% and 99% CL, respectively, assuming a pure Gaussian statistics (e.g., Press et al. 1992). Therefore, we conclude that a mild beaming $b \sim 0.1$ is marginally allowed and stronger beaming is excluded for possibility 1. The flux evolution and comparison with observed data are shown in Figure 4, for the best-fit models with $b = 0.1$ and 1. The result in the isotropic case ($b = 1$) is similar to that of BKC02, as it should be.

A general trend seen in Figure 2 can be understood as follows. When the jet is more strongly collimated, the amount

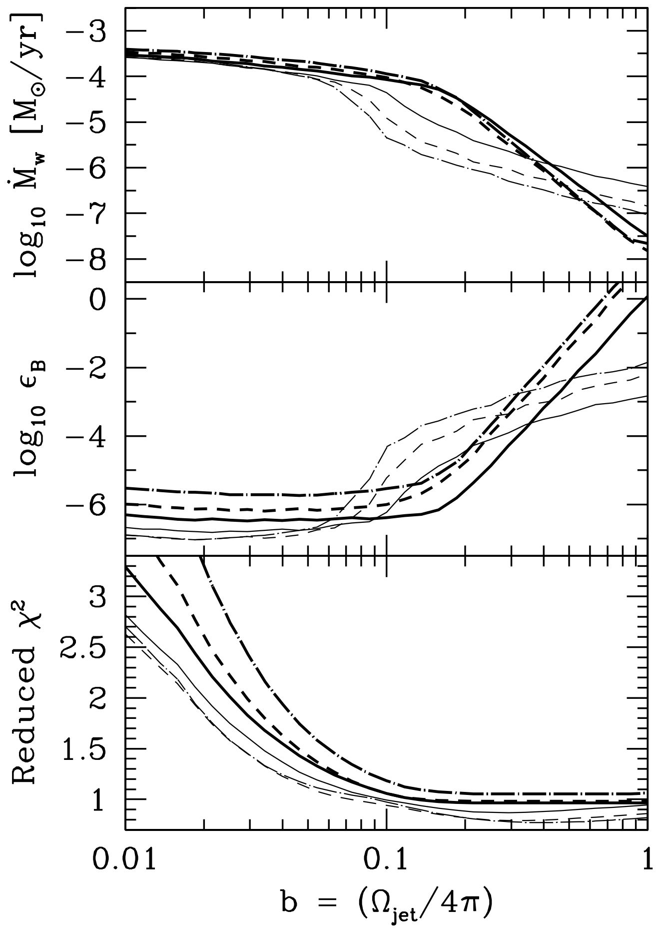

FIG. 2.—Presupernova mass-loss rate $\dot{M}_w$ (*top*), fractional energy density of magnetic field (*middle*), and reduced χ^2 (*bottom*) obtained by χ^2 fitting of the radio emission expected from swept-up CSM by the jet to the observed data. The solid, dashed, and dot-dashed curves are for $p = 2.2$, 2.5, and 2.8, respectively. The low and high values of the minimum electron Lorentz factor, $\gamma_{m,l}$ and $\gamma_{m,h}$, are adopted in calculations for thick and thin curves, respectively.

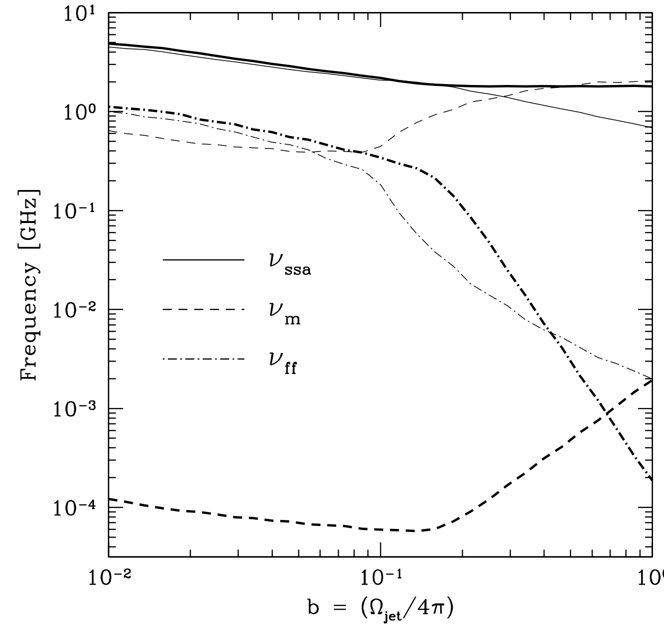

FIG. 3.—Characteristic synchrotron frequency ν_m (*dashed line*), synchrotron self-absorption frequency $\nu_{\rm SSA}$ (*solid line*), and free-free absorption frequency $\nu_{\rm FFA}$ (*dot-dashed line*) at day 7, for the best-fit models to the observed radio flux and spectrum of SN 2002ap. The electron power index is fixed to $p = 2.2$, and thick and thin curves are for the low and high values of γ_m.

of CSM swept up by the jet becomes smaller, and hence a higher mass-loss rate is required to compensate this. However, the observed spectral feature is mostly explained by SSA, and hence the magnetic field must become smaller to keep SSA frequency at the observed value. This explains behaviors between $b = 0.1$ and 1. However, FFA becomes significant when $\dot{M}_w$ becomes very large at $b \lesssim 0.1$. The observed data are not fitted well only by spectral break by FFA because the early rise of radio flux due to decreasing optical depth is more rapid than SSA (see Weiler et al. 1986 for radio supernovae showing this feature), and it does not fit the observed slow rise of radio flux at 1.43 GHz. As a result, $\dot{M}_w$ cannot increase significantly with decreasing b at $b \lesssim 0.1$, and SSA frequency is always higher than FFA for the best-fit models (see Fig. 3). Because of this constraint, the χ^2 rapidly increase with decreasing b smaller than $\sim$0.1. The characteristic frequency ν_m is much smaller than GHz for the low γ_m value, but it becomes close to GHz for the high γ_m value. This provides another freedom to the modeling of the observed spectrum and hence slightly better fits.

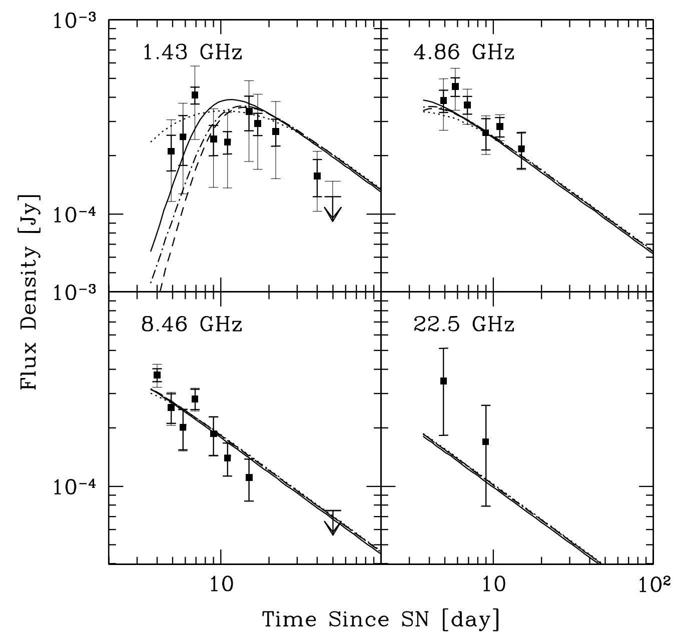

FIG. 4.—Radio flux evolution of the best-fit models for $(b, \gamma_m) = (1, \gamma_{m,l})$, $(1, \gamma_{m,h})$, $(0.1, \gamma_{m,l})$, and $(0.1, \gamma_{m,h})$ (*solid, dotted, dashed, and dot-dashed lines, respectively*). The observed data are from BKC02, with the thick error bars showing observational errors while the thin error bars include the ISS modulation by quadratic sum to the observational errors.

4.2. *Future Emission by Interaction with Wind Bubble or ISM*

When the jet or fast ejecta are interacting with CSM of the stellar wind profile, the synchrotron flux decreases with time even if it is not decelerated. However, it should eventually enter a region where the density is rather uniform. It is either interstellar medium (ISM) that has not been affected by the progenitor star or a uniform density region of CSM such as the stellar wind bubble composed by the shocked wind between the contact discontinuity with ISM and wind termination shock (Weaver et al. 1977; Koo & McKee 1992). If the jet is not yet decelerated in such a uniform density region, the synchrotron radiation flux should be simply proportional to the mass of swept-up CSM/ISM matter and hence should rapidly increase with time as $\propto t^3$, until the jet sweeps up CSM/ISM matter of a comparable mass with the jet itself and deceleration starts.[4] (Note that the cooling frequency of electrons is much higher than the radio bands, and hence cooling does not affect the radio flux.) In the jet hypothesis considered here, this occurs at a time $t_{\rm dec} \sim 13.9 b_{-1}^{-1/3} (n_{\rm ext}/{\rm cm}^{-3})^{-1/3}$ yr after the explosion. Here we assumed that the uniform density region is composed mostly by hydrogen, and $n_{\rm ext}$ is the hydrogen number density. Therefore, once the jet enters the uniform external medium, we expect to see a rapid increase of the radio flux in a timescale of years.

The predicted radio flux by this process is shown in Figure 5, where we used $b = 0.03$ (jet opening angular radius of $\sim 10°$), $p = 2.2$, $\epsilon_e = 0.05$, and $\epsilon_B = 0.01$, which are reasonable values for GRB afterglows (Panaitescu & Kumar 2001), as well as radio supernovae. We suppose possibility 2, and we adopted $\dot{M}_w = 5 \times 10^{-7}\ M_\odot\ {\rm yr}^{-1}$, which is found by BKC02 by isotropic modeling. The calculation is stopped at $t = t_{\rm dec}$, beyond which deceleration must be taken into account. The early radio flux by interaction between the jet and wind profile CSM is smaller than observed with these parameters, as required for possibility 2. Here we assumed that the density profile becomes uniform beyond a radius $r_{\rm ext} = 10^{17}$ or 10^{18} cm and used three values of $n_{\rm ext}$ (0.1, 1, and 10 ${\rm cm}^{-3}$ as typical values for ISM, as well as found in GRB afterglows). There is a discontinuity in the density at $r_{\rm ext}$ depending on $\dot{M}_w$ and $n_{\rm ext}$, but such

[4] It should be noted that the flux does not increase in the case of the stellar wind external profile, as seen in the previous section, even if the total energy of shocked electrons increases as $\propto t$. This is because the magnetic field and hence synchrotron emissivity decrease with time by the scaling assumed between the magnetic energy density and shocked matter.

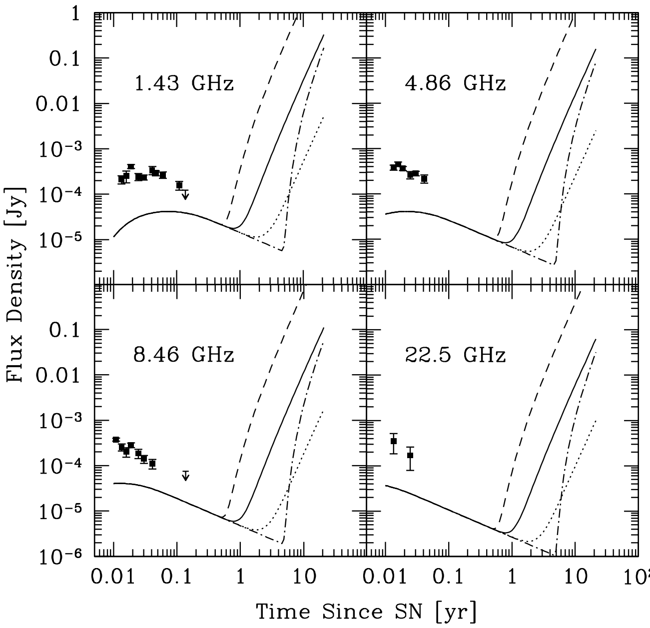

FIG. 5.—Prediction of radio flux by CSM/ISM swept up by the jet in the future. Here we assumed that the observed radio flux (data points from BKC02, error bars not including ISS modulation) is from CSM swept up by isotropic supernova ejecta that are a different component from the jet. The parameters of $(n_{\rm ext}/{\rm cm}^{-3}, r_{\rm ext}/{\rm cm}) = (1,\ 10^{17})$, $(0.1,\ 10^{17})$, $(10,\ 10^{17})$, and $(1,\ 10^{18})$ are used for the solid, dotted, dashed, and dot-dashed lines, respectively.

discontinuity is also expected in reality for stellar wind bubbles (e.g., Weaver et al. 1977).

The transition radius $r_{\rm ext}$ is not easy to estimate, but a calculation of the CSM density profile of presupernova W-R stars indicates $r_{\rm ext} \sim 10^{17}$ cm (Ramirez-Ruiz et al. 2001). Observations of the prototype ring nebular NGC 6888 harboring a W-R star indicate that the wind termination shock is at $\lesssim$1–3 pc within the hot stellar wind bubble (Wrigge, Wendker, & Wisotzki 1994; Moore, Hester, & Scowen 2000). On the other hand, the radio light curves of SN 1998bw can be fitted with the wind density profile up to $\sim$few $\times\ 10^{17}$ cm (Li & Chevalier 1999). Another indirect estimate of $r_{\rm ext}$ is possible from GRB afterglow light curves, assuming that the environment of SN 2002ap is similar to that of typical GRBs. At least some of the GRB afterglow light curves can be fitted better by a model with a homogeneous ambient density profile rather than the wind profile (Chevalier & Li 2000; Panaitescu & Kumar 2002), and such an afterglow light curve seems to start at about 0.1–1 days after the burst, as seen in the latest GRBs (GRB 021004, GRB 021211) with very early optical detections (Holland et al. 2003; Li et al. 2003; Fox et al. 2003). The observer's time is related to the location of the shock of afterglows as

$$r = 3.0 \times 10^{17} (E_{\rm iso}/10^{52}\ {\rm ergs})^{1/4} (n_{\rm ext}/1\ {\rm cm}^{-3})^{-1/4} \times (t_{\rm obs}/0.1\ {\rm days})^{1/4}\ {\rm cm}$$

(e.g., Blandford & McKee 1976), where $E_{\rm iso}$ is the isotropic equivalent energy of GRBs, and beyond this distance the density profile around GRBs seems uniform (see also Holland et al. 2003). Therefore, a plausible scale of $r_{\rm ext}$ is $\sim 10^{17}$–10^{18} cm.

It should also be noted that the speed of isotropic supernova ejecta producing the observed radio flux is inferred to be $\sim 0.3c$ (BKC02), which is comparable to or higher than the inferred jet speed of $0.23c$. Then the isotropic ejecta producing the observed radio flux may be propagating faster than the jet. In this case the jet is not directly interacting with CSM, and the early radio flux prediction in the unshocked stellar wind region is not valid. However, the isotropic supernova ejecta with a speed higher than $0.3c$ are probably a tiny part of the total kinetic energy of the supernova, and hence it will start to be decelerated much earlier than the jet. Then eventually the jet will become the fastest and most distant component among the supernova ejecta, and the radio flux prediction in Figure 5 is valid in such a later epoch.

As expected, the radio flux shows a rapid increase at around $t_{\rm ext} \equiv r_{\rm ext}/(\beta c) = 4.6(r_{\rm ext}/10^{18}\ {\rm cm})(\beta/0.23)^{-1}$ yr. The radio flux would become as strong as $\sim$0.1 Jy. This is not surprising when it is compared with radio GRB afterglows, which have a similar energy scale but much higher expanding speed; typical GRB afterglows would have radio flux of $\sim$1 Jy for years after the burst, if it is placed at a distance of SN 2002ap (Totani & Panaitescu 2002). The expected radio flux for SN 2002ap in the near future is strong enough to detect by a long-term monitoring. Furthermore, jets expanding to two opposite directions (both having $\theta_{\rm obs} \sim 90°$) will have an angular separation of $\theta_{\rm sep} = 20(t/5\ {\rm yr})(\beta/0.23)$ mas, which is easy to spatially resolve by VLBI observations, as proven for SN 1993J (Bartel et al. 1994; Marcaide et al. 1995, 1997). The jet directions should be perpendicular to the observed polarization angle, giving a decisive proof for the jet hypothesis if it is actually detected. On the other hand, nondetection in the next tens of years would not necessarily exclude the jet hypothesis; if the density of the uniform region is low ($n_{\rm ext} \lesssim 0.1\ {\rm cm}^{-3}$) and $r_{\rm ext}$ is large, it would take a long time (greater than or approximately a few tens of years) until the radio emission becomes detectable again.

5. DISCUSSION

5.1. *Implications for the GRB-SN Connection*

The jet inferred from SN 2002ap, having a similar energy scale to GRB jets, should still be regarded as a hypothesis, and we should not overinterpret it at this time. However, since we have shown that the jet is physically possible and it can be tested in the future, it is interesting to think what the jet would mean and how it would fit to the other observational facts obtained so far concerning the GRB-SN connection. Here we suggest a plausible picture for the GRB-SN connection putting together the jet from SN 2002ap and other observational results, assuming that the jet of SN 2002ap is real.

The similarity of the jet energy scale indicates that the SN 2002ap jet is produced by the same mechanism as that for the cosmologically distant GRBs. Then it may be called a "failed" GRB, or another possibility is an off-axis GRB, as mentioned in § 1. Fortunately, we can reject the latter possibility by radio observations made so far. If an off-axis GRB is the case, then we expect even earlier reappearance of radio emission than discussed in § 4.2, which should show even faster expansion with a velocity of $\sim c$ than the jet having a velocity of $\sim 0.23c$. In fact, it is exactly what is called an "orphan afterglow," i.e., a GRB whose jet direction is away from an observer, which can be seen only by late-time, less collimated afterglow emission (for discussions on detectability of radio emission from nearby GRB remnants, see also Paczyński 2001). As shown in Totani & Panaitescu (2002), typical GRB afterglows viewed at a large angle from the jet center at day $\sim$100 should have flux of $\sim$10–100 Jy, $V \sim 16$–18, and $\sim(1$–$10) \times 10^{-12}$ ergs cm^{-2} s^{-1}, in radio (5 GHz), optical, and X-ray (1 keV) bands, respectively, at the distance to SN 2002ap. These fluxes are too faint to detect if it is placed at cosmological distances, but thanks to the close distance to SN 2002ap, we should easily detect an orphan afterglow of SN 2002ap. Then, the latest radio data of SN 2002ap about 200 days after the explosion, which is still at $\sim$0.1 mJy level showing no evidence of flaring up (Berger et al. 2003), already exclude the off-axis GRB possibility.

As discussed in § 3.4, the decay gamma ray of ^{56}Ni is the most likely ionization process of the jet from SN 2002ap, but the required amount of ^{56}Ni in the jet and/or outside the photosphere is difficult to explain only by hydrodynamical instability. Hence, this indicates that the jet is formed and ejected from the central region of the core collapse. On the other hand, we do not expect a sufficient amount of ^{56}Ni for ionization, if the jets are formed at the outer envelope of the star, such as transrelativistic acceleration of the shock wave when it passes through the steep density gradient of the stellar surface, as studied by Matzner & McKee (1999) and Tan, Matzner, & McKee (2001).[5]

On the other hand, considering the similarity between SN 2002ap and SN 1998bw/GRB 980425, we may also want to establish a consistent picture including GRB 980425, which is peculiar in a few points compared with GRBs found at cosmological distances. GRB 980425 has a soft spectrum and a smooth temporal profile (such as long spectral lag), and its total isotropic-equivalent energy is about 10^4 times smaller than typical GRBs at cosmological distances (Bloom et al. 1998; Norris, Marani, & Bonnell 2000). One possible interpretation of these properties is that this is a typical GRB, but we observed this event at a slightly off-axis direction from the jet center (Nakamura 1999; Ioka & Nakamura 2001; Salmonson 2001; Granot et al. 2002). However, if GRB 980425 is a normal but off-axis luminous GRB, we expect orphan afterglow radiation after it became mildly relativistic. Although optical afterglow radiation may be hidden by the brightness of SN 1998bw (Granot et al. 2002), radio afterglow flux expected for typical GRBs at a distance to SN 1998bw is 0.4–4 Jy at $t \sim 100$ days (Totani & Panaitescu 2002), which is still much larger than actually observed ($\sim$10 mJy at day 100), even though SN 1998bw was much brighter than SN 2002ap. In addition to this, Norris (2002) identified a subclass of GRBs including GRB 980425, whose members have low luminosity, long spectral lags, and soft spectrum. These low-luminosity GRBs tend to have just a few wide pulses, while nearly all high-luminosity GRBs have many, narrow pulses, indicating that only the viewing angle effect cannot explain the difference between the low- and high-luminosity GRBs.

Here we note our result that the radio emission from SN 2002ap cannot be strongly collimated. Polarization was not detected for the strong radio emission of SN 1998bw, indicating that the radio emission is produced by isotropic ejecta (Kulkarni et al. 1998). The high-velocity shell responsible for radio flux of SN 1998bw shows evidence of deceleration (Li & Chevalier 1999), and hence the kinetic energy of the shell should not be much larger than $\sim 10^{49}$ ergs. GRB 980425 associated with SN 1998bw has an isotropic equivalent energy of about $\sim 10^{48}$ ergs, which is very different from the standard energy scale of cosmologically distant GRBs but is close to that of the isotropic radio-emitting shell.

Tan et al. (2001) have shown that the peculiar GRB 980425 can be produced by the isotropic fast shell produced by the hydrodynamical shock acceleration, which is the same shell producing radio emission. The smooth temporal profile of GRB 980425 may also be expected by the isotropic shock acceleration process. Even if explosion is highly asymmetric at the center, a two-dimensional simulation by Maeda et al. (2002) indicates that the outer low-density region is rather isotropic. The efficiency of the shock acceleration sensitively depends on the outer density profile of the stellar envelope (Tan et al. 2001), and it may not be surprising even if SN 1998bw and SN 2002ap produced very different velocities and energies of fast-moving isotropic ejecta.

Then, the apparent discreteness between GRB 980425 and other GRBs may be understood by two distinct driving processes of GRBs: cosmologically distant GRBs are strongly collimated jets with an energy scale of $\sim 10^{50}$–10^{51} ergs, which is produced along with ejection of ^{56}Ni outside the photosphere by the central activity of core collapses (referred to as type 1 for convenience), while GRB 980425 is produced by much less energetic, isotropic fast ejecta, which could be produced by hydrodynamic shock acceleration at the outer layer of exploding stars (type 2). There is a possibility that SN 1998bw was successful also as an off-axis type 1 GRB, but this possibility is not favored by the nondetection of radio orphan afterglow showing an energy scale of $\sim 10^{51}$ ergs for $\sim$300 days, as mentioned above.

Other past events of Type Ic supernovae may also have produced energetic jets with a velocity of $\sim 0.2c$, like SN 2002ap. Such jets, if they exist, may now be emitting strong radio emission after sweeping up enough amounts of ISM/CSM, showing jetlike morphology. We note that the timescale of emergence in radio wavelength could be much longer for the case of a failed GRB with low-speed jets than considered in previous publications for off-axis GRBs or GRB remnants (Paczyński 2001). On the other hand, it would be shorter than the timescale of establishment of normal radio supernova remnants, corresponding to the transition from the free expansion to the Sedov-Taylor phase ($\sim$100 yr). Reexamination and new follow-up of such past Type Ic events are encouraged.

The picture of GRB-SN connection presented here predicts that all type 1 GRBs should be associated with energetic Type Ib/Ic supernovae (as confirmed by SN 2003dh/GRB 980329 after the submission of this paper), but we expect a variety of supernova luminosity that may not be correlated with GRB luminosity or the jet energy. The supernova luminosity is determined by the amount of synthesized ^{56}Ni within the photosphere where the radioactive energy is converted into optical photons. As we suggested, the jet formation activity may eject a significant amount of ^{56}Ni well outside the photosphere, where ^{56}Ni cannot contribute to the optical luminosity. This is not inconsistent with the results of searches for supernova evidence in GRB afterglows (Bloom et al. 1999, 2002; Galama et al. 2000; Reichart 2001; Garnavich et al. 2003; Price et al. 2003).

[5] Following Tan et al. (2001), we use "hydrodynamical shock acceleration" for this phenomenon, which must not be confused with the Fermi acceleration of cosmic-ray particles.

5.2. *On the X-Ray Line Features in GRB Afterglows*

Emission-line features of iron (or nickel) and multiple-alpha nuclei (Mg, Si, S, Ar, Ca, etc.) are often found in X-ray GRB afterglows on a timescale of $\sim$1 day (Piro et al. 1999, 2000; Yoshida et al. 1999; Antonelli et al. 2000; Reeves et al. 2002; Butler et al. 2003). Theoretical explanations mostly fall into two categories: (1) the geometry-dominated (GD) scenario where the timescale of $\sim$1 day is attributed to the photon propagation time; this scenario needs a supernova explosion that occurred weeks prior to a GRB (the supranova model; Vietri et al. 2001), dense pre-burst circumstellar material (Weth et al. 2000; Kotake & Nagataki 2001), or a distant reflector of GRB/afterglow emission such as an $e^{\pm}$-pair screen (Kumar & Narayan 2003); and (2) the engine-dominated (ED) model where a long-lived energy source left over in the center of the star after the GRB is ionizing the matter around it (Rees & Mészáros 2000). Most of these explanations assume that the ionization process is photoionization by GRB/afterglow radiation or long-lived remnants, while an alternative is shock heating around the center (Böttcher 2000). However, all these scenarios have one or more problems (Lazzati, Ramrez-Ruiz, & Rees 2002; Kumar & Narayan 2003), and other possible explanations are still worth seeking.

Here we propose that the ionization by radioactivity of decaying ^{56}Ni in the mildly optically thin region, which has been suggested as the ionization mechanism for the SN 2002ap jet, can be considered as a new explanation for the X-ray line features of afterglows. First, let us check the energetics. The luminosity of decaying energy is given by $\sim 1.0 \times 10^{44} (M_{\rm Ni}/M_\odot)$ ergs s^{-1} within $\sim t_{\rm Ni} = 8.1$ days after the explosion. We need several solar mass of ^{56}Ni to explain the luminosities of X-ray line features; this is admittedly large compared with typical supernovae, and here we have assumed 100% efficiency for the energy conversion from radioactive decay into line photons, which seems rather extreme. However, we know that SN 1998bw produced about $\sim 1\ M_\odot$ of nickel, and it seems not very unlikely that more massive and energetic supernova (or hypernova) events produce even more nickel than SN 1998bw and eject it out to the relatively optically thin region, via the process of jet formation for type 1 GRBs. If radioactive gamma rays lose their energy dominantly by ionizing nearby ions, efficiency of line production could be close to unity in some preferred situations.

If all ^{56}Ni ions are fully ionized, the radioactive decay by electron capture is impossible (McLaughlin & Wijers 2002), but repeated decays and ionizations would be possible if the recombination rate is sufficiently high. This is a complicated process, and clearly more careful and quantitative study is required to support this speculation.

This scenario can be considered as a new type of ED explanations that do not need a supernova prior to a GRB, but it has one important difference from previous ones: this scenario does not require a strong radiation source in X-ray band for ionization, but high-energy electrons produced by scattering of decay gamma rays directly ionize ions, and hence we might expect high equivalent width with weak continuum radiation. In this way the major problem of ED scenarios, i.e., that we should have directly observed stronger ionizing radiation or bremsstrahlung continuum of shock-heated matter than actually observed (Lazzati et al. 2002; Kumar & Narayan 2003), might be avoided.

The timescale of line production should be determined by evolution of physical conditions by expansion, such as optical depth, density, and recombination rates. Note again that radioactive ionization should be efficient only in a small range of optical depth where it is mildly optically thin, and then we expect a shorter timescale of line production than the typical peak of supernova light curve that is determined by diffusion of radiation within the photosphere, and it might become even shorter than the timescale of ^{56}Ni decay.

6. SUMMARY AND CONCLUSIONS

We have shown that the jet hypothesis proposed by Kawabata et al. (2002) for SN 2002ap based on their spectropolarimetric observation at day $\sim$13 is physically possible and consistent with all observations. We estimated the jet mass ($\sim 0.01\ M_\odot$), direction (approximately perpendicular to the observer), and energy ($\sim 5 \times 10^{50}$ ergs) by a fully relativistic treatment. The large jet energy does not contradict the weak radio flux, since the jet is almost freely expanding and jet material is not yet shocked. The total energy of electrons inferred from synchrotron radio flux, $\sim 10^{45}$ ergs, only reflects that of CSM swept up and shocked by jet or high-speed ejecta from SN 2002ap. The jet becomes optically thin on a timescale of 5–10 days, and weak continuum polarization found by the earlier VLT observation at day $\sim$5 can be explained by high optical thickness of the jet to electron scattering.

The jet must be substantially ionized to reproduce the redshifted polarized continuum. Rapid adiabatic loss of the jet internal energy should have cooled down the jet material below the temperature required for the jet to be kept ionized, and hence external heating or a photoionization source is necessary. We have shown that photoionization is quite unlikely by any sources, and the most likely ionization process is heating by decaying ^{56}Ni when the jet is mildly optically thin. Still, ionization is not easy; the jet must have a mass fraction of order unity of ^{56}Ni or a larger amount of ^{56}Ni outside the photosphere that is at least comparable with that within the photosphere ($\sim 0.07\ M_\odot$), which is difficult to explain simply by hydrostatic instability. This result indicates that the jet must be formed and ejected from the central region of the core collapse.

We examined whether the observed radio emission can be explained by CSM swept up by the jets, and we found that the radio data favor isotropic ejecta. Jets with $b \equiv (\Omega_{\rm jet}/4\pi) \sim 0.1$ are marginally possible to explain the radio data, and stronger collimation is excluded as the origin of the observed radio emission. If the jet is strongly collimated, the radio emission must be from isotropic fast ejecta that are a different component from the jet.

The jet should still be regarded as a hypothesis, but we predict that, if the jet hypothesis is the case, the jet would eventually pass through the unshocked presupernova wind region ($\rho \propto r^{-2}$) and enter a region where the CSM/ISM density is rather uniform. The jet mass is large enough not to be decelerated until it sweeps up a comparable mass of ISM/CSM in a few to $\sim$10 yr. Then we expect a rapid increase of radio flux that should easily be detected by future long-term radio monitoring, with reasonable parameters for ISM/CSM density and profile. Fortunately, such radio emission can be resolved spatially by a VLBI observation, and the morphology and jet direction relative to the observed polarization angle would give a clear proof of the jet hypothesis.

Although it is a speculation that would become effective when the jet hypothesis is confirmed by future observations, we discussed how the inferred jet would fit our knowledge about the GRB-SN connection, taking into account various observational facts obtained in the past. To explain all the observations consistently, we suggest two distinct classes of GRBs by different formation processes but from similar core-collapse events; cosmologically distant GRBs are produced by strongly collimated jets having an energy scale of $\sim 10^{50}$–10^{51} ergs, which are produced and ejected from the central region of the core collapse. The SN 2002ap jet can be considered a failed GRB of this class, with much larger baryon load than typical successful GRBs. ^{56}Ni is ejected from the center along with the jet, which is responsible for the ionization of the SN 2002ap jet. Such ^{56}Ni may also explain the X-ray line features often found in GRB afterglows, depending on the amount of ^{56}Ni and physical conditions, although a more quantitative study is required to verify this possibility. On the other hand, the peculiar GRB 980425 and radio emission from SN 1998bw and SN 2002ap that seems isotropic may be produced by isotropic and much less energetic ejecta, which could be formed by the hydrodynamical shock acceleration at the surface of an exploding star.

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