On the Nonthermal Emission from the Supernova Remnant W51C

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ABSTRACT

The middle-aged supernova remnant (SNR) W51C is an interesting source for the interaction of the shell with a molecular cloud. The shell emits intense radio synchrotron photons, and high-energy gamma-rays from the remnant have been detected using the Fermi Large Area Telescope (LAT), the H.E.S.S. telescope, and the Milagro gamma-ray observatory. Based on a semi-analytical approach to the nonlinear shock acceleration process, we investigate the multiband nonthermal emission from W51C. The result shows that the radio emission from the remnant can be explained as synchrotron radiation of the electrons accelerated by a part of the shock flowing into the ambient medium. On the other hand, the high-energy gamma-rays detected by the Fermi LAT are mainly produced via proton-proton collisions of the high-energy protons with the ambient matter in the molecular cloud overtaken by the other part of the shock. We propose a possible explanation of the multiband nonthermal emission from W51C, and it can be concluded that a molecular cloud overtaken by a shock wave can be an important emitter in GeV γ-rays.

Key words: gamma rays: theory - ISM: individual (W51C) - supernova remnant

1 INTRODUCTION

SNRs are broadly thought as the primary accelerators of the Galactic cosmic rays accelerated through diffusive shock acceleration in the shock waves (e.g., Blandford & Eichler 1987, Berezhko & Völk 2007). Observations of SNRs in the high-energy γ-ray band provide evidence for acceleration of particles to relativistic energies (e.g., Aharonian et al. 2008c). However, both electrons and nuclei can be accelerated to relativistic energies, and the high-energy γ-rays from SNRs can usually be explained either as proton-proton (p-p) interaction between the relativistic protons and the ambient matter or as inverse Compton scattering of the electrons on the soft photons (e.g., Yamazaki et al. 2008; Aharonian et al. 2007, 2008; Fang et al. 2008, 2009; Zirakashvili & Aharonian 2010). The interpretation of the γ-rays produced via the inverse Compton scattering makes the evidence of the argument that the nuclei in the cosmic rays are accelerated by the SNR shells indirectly.

P-p collisions can be greatly enhanced if a SNR shell interacts with a molecular cloud, and observations of γ-rays from this system provide evidence of the nuclei in the cosmic rays being accelerated by SNRs (e.g., Aharonian et al. 1994). Moreover, γ-rays from such systems have probably been detected with H.E.S.S. (e.g., Aharonian et al. 2008a, b) and EGRET (Hartman et al. 1999).

The SNR W51C appears as a partial shell of ∼30′ diameter in the radio continuum with an open northern part (Moon & Koo 1994). From the observations of the two 1720 MHz OH masers toward the north of the shell (Green et al. 1997) and the detection of shocked atomic and molecular gases in this direction (Koo & Moon 1997a, b), it is argued that this remnant is interacting with a molecular cloud.

Both shell-type and center-filled morphologies were indicated in the X-ray observations with ROSAT, and an age of ∼3 × 10^4 yr and an explosion energy ∼3.6 × 10^51 erg were estimated based on the Sedov or the evaporation models (Koo et al. 1995). An extended source, CXO J192318.5+1403035, composed of a relatively bright core surrounded by a diffuse envelope was discovered with ASCA (Koo et al. 2002), and it was also detected with Chandra (Koo et al. 2003). The core-envelope structure and its spectral properties suggest that the source is a pulsar wind nebula (PWN) associated with the SNR 51C, and a putative pulsar is argued to exist inside it.

In TeV γ-rays, an extended source HESS J1923+141 coincident with W51C have been found using H.E.S.S. (Fiasson et al. 2009). Moreover, Abdo et al. (2009a) recently reported a possible excess of multi-TeV gamma-rays towards W51C with a flux of 39.4 ± 11.5 × 10^{-17} TeV^{-1} cm^{-2} s^{-1} at 35 TeV from the Milagro observation. Further-
more, the GeV γ-rays from the SNR, which is known to be interacting with a molecular cloud, with a luminosity of \( \sim 1 \times 10^{37} \text{ erg s}^{-1} \) for a distance of 6 kpc, have been detected with the LAT on board the Fermi Gamma-ray Space Telescope (Abdo et al. 2009). The γ-ray spectrum cannot be fitted with a single power law and steepens above a few GeV. Abdo et al. (2009b) discussed the nonthermal radiative properties of the radio emission and γ-rays from the SNR using a broken power-law with the same index for the momentum distribution of the radiating electrons/protons. Their result shows that p-p interaction is more likely the main process to produce the observed γ-rays since the observed radio synchrotron spectrum cannot be well reproduced in the bremsstrahlung-dominated case and an origin of inverse Compton scattering for the γ-rays needs a low density of hydrogen (\(< 0.1 \text{ cm}^{-3}\)) in the SNR, which conflicts with the constraints from observations in the radio and X-ray bands.

Semi-analytical methods to the nonlinear diffusive shock acceleration process have been widely used to investigate the nonthermal radiative properties of SNRs (e.g., Morlino et al. 2009; Fang et al. 2009; Ellison et al. 2010). In this paper, we study the nonthermal radiative properties of the SNR W51C based on a semi-analytical method (Blasi 2002; Amato, Blasi & Gabici 2008), where the pitch-angle averaged steady-state distribution of the radiating electrons/protons.

\[
\frac{\partial f}{\partial x} + u \frac{\partial f}{\partial x} + \frac{1}{3} \frac{d u}{d p} \frac{\partial f}{\partial p} = Q(x, p) = 0, \quad (1)
\]

where the coordinate \( x \) is directed along the shock normal from downstream to upstream, \( D \) is the diffusion coefficient and \( u \) is the fluid velocity in the shock frame, which equals \( u_2 \) downstream (\( x < 0 \)) and changes continuously upstream, from \( u_1 \) immediately upstream (\( x = 0^+ \)) of the subshock to \( u_0 \) at upstream infinity (\( x = +\infty \)). For the Bohm diffusion, \( D = \frac{pe^2}{3\epsilon B} \), where \( B \) is the local magnetic field strength. With the assumption that the particles are injected at immediate upstream of the subshock, the source function can be written as \( Q(x, p) = Q_0(p) \delta(x) \). For monoenergetic injection, \( Q_0(p) \) is

\[
Q_0(p) = \frac{\eta n_{\text{gas}} \epsilon_{\text{inj}} U_{\text{inj}}}{4\pi p_{\text{inj}}^2} \delta(p - p_{\text{inj}}), \quad (2)
\]

where \( p_{\text{inj}} \) is the injection momentum, \( n_{\text{gas}} \) is the gas density at \( x = 0^+ \) and \( \eta \) is the fraction of particles injected in the acceleration process. With the injection known as thermal leakage, \( \eta \) can be described as

\[
\eta = \frac{4(R_{\text{sub}} - \epsilon_0) e^{-\epsilon_0^2/2\Gamma^2}}{\sqrt{2\pi}} \quad \text{Blasi, Gabici & Vannoni 2008; Amato, Blasi & Gabici 2008,}
\]

where \( R_{\text{sub}} = u_1/u_2 \) is the compression factor at the subshock and \( \xi \) is a parameter of the order of 2–4 describing the injection momentum of the thermal particles in the downstream region (\( p_{\text{inj}} = \xi p_{\text{inj}} \)). We use \( \xi = 3.5 \) as in Amato, Blasi & Gabici (2008), \( p_{\text{inj}} = (2m_p k_B T_0)^{1/2} \) is the thermal peak momentum of the particles in the downstream fluid with temperature \( T_0 \), \( m_p \) is the proton mass and \( k_B \) is the Boltzmann constant. Assuming the heating of the gas upstream is adiabatic, with the conservation condition of momentum fluxes between the two sides of the subshock, we can derive the relation between the temperature of the far upstream \( T_0 \) and \( T_2 \), i.e., \( T_2 = (\gamma_2 M_0^2/R_{\text{tot}})\left[R_{\text{sub}}/R_{\text{tot}} - 1/R_{\text{tot}} + (1/\gamma_2 M_0^2)\left(R_{\text{sub}}/R_{\text{tot}}\right)^\gamma\right] T_0 \), where \( M_0 \) is the Mach number far upstream, \( R_{\text{tot}} = u_0/u_2 \) is the total compression factor, \( \gamma_2 \) is the ratio of specific heats (\( \gamma_2 = 5/3 \) for an ideal gas)

Particles with larger momenta move farther away from the shock than those with lower momenta, only particles with momentum \( \geq p \) can reach the point \( x_0 \), (see details in Blasi 2002), and thus the pressure of the accelerated particles at the point can be described as

\[
P_{\text{Cu}, p} = \frac{4\pi}{3} \int_{p_0}^{p_{\text{max}}} dp' p'^{5/2} v(p') f_0(p') , \quad (3)
\]

where \( v(p) \) is the velocity of particles with momentum \( p \). Furthermore, the particle distribution function \( f_0(p) \) at the shock can be implicitly written as (Blasi 2002)

\[
f_0(p) = \left\{ \frac{3R_{\text{tot}}}{R_{\text{tot}} U(p) - 1} \right\} \frac{n_{\text{ism}}}{4\pi p_{\text{inj}}} \exp \left[ -\int_{p_{\text{inj}}}^{p_{\text{max}}} \frac{dp'}{p'} \frac{3R_{\text{tot}} U(p') - 1}{R_{\text{tot}} U(p') - 1} \right] , \quad (4)
\]

where \( n_{\text{ism}} \) is the gas density far upstream (\( x = +\infty \)), \( p_{\text{max}} \) is the maximum momentum of the accelerated protons, and it can be estimated as (Lagage & Cesarsky 1983; Aharonian & Atwood 1999)

\[
p_{\text{max}} = 5.3 \times 10^4 \left( \frac{B}{10^3 \mu G} \right) \left( \frac{u_0}{10^9 \text{cm s}^{-1}} \right)^2 m_p c_9 \quad (5)
\]

for a "Bohm limit" according to the standard diffusive shock acceleration theory, where \( B \) the magnetic field strength, \( t_3 \) is the age of the host SNR in units of \( 10^3 \) yr. \( U(p) \) can be solved using an equation deduced from the conservation of the mass and momentum fluxes with the boundary condition \( U(p_{\text{inj}}) = R_{\text{sub}}/R_{\text{tot}} \) and \( U(p_{\text{max}}) = 1 \), and then a value of \( R_{\text{sub}} \) can be achieved by an iterative procedure to satisfy the boundary conditions (Blasi 2002).

The electrons have the same spectrum of the protons up to a maximum energy determined by synchrotron losses, and the spectrum can be described as (e.g., Fang et al. 2003)

\[
f_e(x, p) = K_e f_0(x, p) \exp(-E(p)/E_{\text{max}, e}), \quad (6)
\]

where \( E(p) \) is the kinetic energy of the electrons, and the electron/proton ratio \( K_e \) is treated as a parameter. By equating the synchrotron loss time with the acceler-
where the cutoff energy $E_{\text{max},e}$ can be estimated as (Berezhko et al. 2002)

$$E_{\text{max},e} = 6 \times 10^7 \left( \frac{n_0}{10^6 \text{cm}^{-3}} \right) \left( \frac{R_{\text{tot}} - 1}{R_{\text{tot}}(1 + R_{\text{sub}} R_{\text{tot}})} \right)^{1/2} \left( \frac{10 \mu \text{G}}{B} \right) \text{s}^{-1}$$

Assuming the accelerated particles distribute homogeneously and most of the emission is from downstream of the shock, and using the distribution function at the shock to represent the particle distribution in the whole emitting zone, the volume-averaged emissivity for photons produced via p-p interaction can be written as

$$Q(E) = 4\pi n_{\text{gas}} \int dE_p J_p(E_p) \frac{d\sigma(E, E_p)}{dE},$$

(8)

where $E_p$ is the proton kinetic energy, $n_{\text{gas}}$ is the ambient gas number density, and $J_p(E_p) = v p^2 f_0(p) dp/dE_p$ is the volume-averaged proton density and $v$ is the particles’ velocity. We use the differential cross-section for photons $d\sigma(E, E_p)/dE$ presented in (Kamae et al. 2000) to calculate the hadronic $\gamma$-rays produced via p-p collisions. Finally, the photon flux observed at the earth can be obtained with

$$F(E) = \frac{V Q(E)}{4\pi d^2},$$

(9)

where $d$ is the distance from the earth to the source and $V$ is the average emitting volume of the source and can be estimated by $V \approx (4\pi/3) R_{\text{tot}}^3 / R_{\text{tot}}$ (Ellison et al. 2000), here $R_{\text{tot}}$ is the radius of the SNR.

The SNR W51C has an age of $\sim 3 \times 10^4$ yr (Koo et al. 2003) and a radius of $\sim 30$ pc for a distance of 6 kpc (Moon & Koo 1994). With $d = 6$ kpc, $R_{\text{tot}} = 30$ pc, $T_{\text{up}} = 0.5 \times 10^6$ K, and $p_{\text{max}} = 10^{12}$ m$_c$, the resulting proton spectra and the spectral energy distribution of the p-p collisions for the protons with different Mach number are illustrated in Fig.1. The results are weakly sensitive to the temperature upstream of the shock, and a temperature of $0.5 \times 10^6$ K is used in the calculation, which corresponds to a sound speed of 83 km s$^{-1}$. The observed results with the Fermi LAT (Abdo et al. 2009a), H.E.S.S. (Fassion et al. 2009), and Milagro (Abdo et al. 2009a) are shown in the figure for comparison. For each $M_0$, $n_{\text{ism}}$ is normalized to make the resulting flux at 9 GeV consistent with the one observed by the Fermi LAT. The flux points for the SNR W51C obtained with the Fermi LAT (Abdo et al. 2009a), H.E.S.S. (Fassion et al. 2009), and Milagro (Abdo et al. 2009a) are shown in the figure for comparison.

![Figure 1](nonthermal-emission-w51c.png)

**Figure 1.** The resulting proton spectra (upper panel) and the spectral energy distribution of photons from the p-p collisions (lower panel) for $M_0 = 15$, $n_{\text{ism}} = 0.34$ cm$^{-3}$ (solid line); $M_0 = 10$, $n_{\text{ism}} = 0.53$ cm$^{-3}$ (dashed line); $M_0 = 5$, $n_{\text{ism}} = 1.51$ cm$^{-3}$ (dotted line); and $M_0 = 2.8$, $n_{\text{ism}} = 14.4$ cm$^{-3}$ (dash-dotted line). The other parameters are $d = 6$ kpc, $R_{\text{tot}} = 30$ pc, $T_{\text{up}} = 0.5 \times 10^6$ K, and $p_{\text{max}} = 10^{12}$ m$_c$. For each $M_0$, $n_{\text{ism}}$ is normalized to make the resulting flux at 9 GeV consistent with the one observed by the Fermi LAT. The flux points for the SNR W51C obtained with the Fermi LAT (Abdo et al. 2009a), H.E.S.S. (Fassion et al. 2009), and Milagro (Abdo et al. 2009a) are shown in the figure for comparison.

The SNR shell is interacting with the MC. As a result, the velocity of this part of the shell decreases significantly, and the observed $\gamma$-rays can be reproduced as p-p collisions accelerated in this part of the shell due to its low Mach number.

The other part of the shell can freely expand into the interstellar medium with a relatively low density. Therefore, we assume about $f = 0.4$ of the SNR shell transports into the MC with a Mach number of 2.8 now, and the other part of the shell have a relatively large Mach number, $M_0 = 10$, corresponding to a shock speed of 830 km s$^{-1}$ for $T_{\text{up}} = 0.5 \times 10^6$ K. The synchrotron photons in the lower energy band are attenuated via free-free absorption in the journey from the source to the earth, and the absorption coefficient can be described as (Ginzburg & Syrovatskii 1969)

$$\alpha_{\text{ff}}(\nu) = 10^{-2} \frac{n_e^2}{\nu^2} \left( \frac{T_\text{e}}{\nu} \right)^{3/2} \left. 17.7 + \ln \left( \frac{T_\text{e}^{3/2}}{\nu} \right) \right|,$$

(10)

where $\nu$ is the electron frequency, $n_e$ and $T_\text{e}$ are the density and temperature of the intervening ISM, respectively. We use $T_\text{e} = 8000$ K and $n_e d = 9.3 \times 10^{22}$ cm$^{-2}$ for W51C. The resulting multiband nonthermal emission for the two parts of the shell are shown in Fig.2. The soft photons involved in the inverse Compton scattering include the cosmic mi-
The observed emission with a shell-type morphology in the radio band from W51C can be explained as the synchrotron radiation from the electrons in the shell not encountered by the MC with a Mach number of 10. A magnetic field strength > 100 μG is usually derived for SNRs (e.g., Parizot et al. 2006; Tanaka et al. 2008). With B = 150 μG, the maximum energy of the protons is ∼ 1.6 × 10^13 TeV (Eq. 5) for an age of 3 × 10^5 yr, which is near the “knee” energy of the Galactic cosmic rays. With a density of n_{ism} = 0.08 cm^-3, the resulting flux from p-p interactions at 35 TeV is consistent with the observation with Milagro. The electron to proton ratio K_{ep} cannot be theoretically determined now, which is usually treated as a parameter limited by the comparison of the resulting flux from the model with the observations for a given source (e.g., Berezhko et al. 2002; Mironov et al. 2009; Fang et al. 2008, 2009; Zirakashvili & Aharonian 2010). Its value can be from ∼ 10^{-1} for young SNRs to ∼ 10^{-2} for old ones (Zirakashvili & Aharonian 2010). In our model with M_0 = 10 and B = 150 μG for the part of the shell of W51C not colliding with the MC, the radio must be 2 × 10^{-2} to have the detected radio emission explained as the synchrotron radiation of the electrons, which is about twice the value in the galactic cosmic rays at 10 GeV around the earth. In order to produce the observed fluxes in the radio bands, the ratio K_{ep} cannot be very smaller than 0.02 except a much stronger magnetic field is used. In such a case, the emission above 1 TeV is dominated by p-p interactions of the accelerated particles containing a kinetic energy of 3.4 × 10^{50} erg, and the TeV photons at 35 TeV observed with Milagro are from this mechanism (see the upper panel in Fig. 2). The maximum energy of the accelerated electrons is 1.7 TeV (Eq. 6). With the free-free absorption taken into account, the detected fluxes in the radio band can be reproduced with the synchrotron radiation of the accelerated electrons.

For the part of the SNR shell interacting with the MC, with M_0 = 2.8, n_{ism} = 21.4 cm^-3 is needed to make the resulting flux of p-p collisions consist with that at 9 GeV detected with the Fermi LAT. The flux from the accelerated electrons is sensitive to the electron to proton ratio K_{ep}, which is set to 2 × 10^{-2} as for the part not interacting with the MC. With this ratio, the magnetic field downstream of the shock cannot be much larger than 15 μG to avoid the resulting synchrotron flux to conflict with the observed flux points in the radio band. In such a case, the maximum energies of the electrons (E_{max,e}) and the protons (E_{max,p}) are 3.0 and 12 TeV, respectively. With these reasonable parameters, the high-energy γ-ray spectrum of the SNR W51C observed with the Fermi LAT and H.E.S.S. can be well reproduced (see the lower panel in Fig. 2). These γ-rays are mainly produced via p-p interaction between the protons in the shell interacting with the MC and the ambient matter, and the kinetic energy contained in the protons is about 5 × 10^{50} erg.

There are uncertainties on the parameters we used to reproduce the multiband observed flux points for the SNR W51C in our model. For instance, the value of the ambient density is sensitive to the Mach number and the whole number of the accelerated particles, which is determined by the emitting volume with a known spectra of the accelerated protons. In this paper, the ratio of the shell colliding with the ambient MC is assumed to be f = 0.4 based on the observed extension of the γ-rays is similar as that in the radio continuum. For the part of the shell interacting with the remnant, a Mach number of 2.8 is derived to make the resulting fluxes from p-p collisions consist with the shape of the flux obtained with the Fermi LAT. With such a Mach number, a density of n_{ism} = 21.4 cm^-3 is needed to reproduce the observed flux of the γ-ray band. The distribution of the protons is ∝ n_{ism}, and this relation is also valid for the rate of p-p interaction. As a result, we can only limit the value f n_{ism} from equaling the resulting flux of p-p interactions to the observed one, and the density varies from 25 cm^-3 for f = 0.3 to 19 cm^-3 for f = 0.5. Moreover, the error of the observed γ-ray fluxes is about 50%, and then the observed γ-rays are from this mechanism (see the upper panel in Fig. 2).
uncertainty of $n_{\text{min}}$ limited in our model is about 6.0 cm$^{-3}$ for $f = 0.4$.

3 DISCUSSIONS AND SUMMARY

W51C is an interesting source for the interaction of the shell with the MC from the observations of OH masers and shocked atomic and molecular gases in the direction of the source. It is also the first SNR detected in the Fermi LAT in the GeV band. The SNR appears a shell-type morphology, whereas the GeV signals are clumpy and extended within the radio shell. The $\gamma$-rays steep above several GeV, and the spectrum cannot be reproduced via p-p collisions with an index of $\sim 2.0$ for the relativistic protons. Cosmic ray electrons with a power-law spectrum can be easily steepened by unity due to losses (Kardashev 1962), and it is plausible that this steepening can be explained in the scenario of a power-law electrons encountering significant losses. However, the multiband nonthermal radiative properties of W51C have also been studied by Abdo et al. (2009) using a broken power-law spectrum for the energy distribution of the electrons/protons. They found the observed flux points in the radio and GeV bands cannot be well reproduced by assuming the radio emission and high-energy $\gamma$-rays are produced by the same population of electrons, and only in the pioneering scenario in which the $\gamma$-rays are produced by the protons can the multiband spectrum be well fitted. Moreover, it seems unlikely that the GeV signals are from the PWN powered by the putative pulsar (Koo et al. 2005) because the nebula is much smaller with a few pc extension in X-rays compared with the GeV source and its radio emission is much weaker (Abdo et al. 2009b).

We model the source in the case that one part of the shell transports into the MC with dense matter and the other part expands into the interstellar space with a relatively small density. The spectra of the particles in the two parts of the shell are treated in a semi-analytical approach to the nonlinear shock acceleration. Note that in this paper the shock structure is assumed to be quasi-parallel rather than quasi-perpendicular. The maximum energy of the protons accelerated in the quasi-perpendicular shocks can be significantly higher than that in the quasi-parallel cases with a much smaller perpendicular diffusion efficient compared with the parallel one, and a quasi-parallel shocks cannot possibly be true over all of $4\pi$ (Jokipii 1983). The contribution of the secondary $e^{\pm}$ pairs produced from p-p interactions on the nonthermal emission is not taken into account in this paper. Including it needs a time-dependent model to describe the evolution history of the SNR and the collision between the part of the shock and the MC, and this complicated process could bring more assumptions in the model; moreover, with $K_{\text{sp}} = 2 \times 10^{-2}$, the emission of the secondary pairs is usually insignificant compared with that from the accelerated electrons. In fact, the multiband observed spectrum can be reproduced with our model, thus we do not take into account the emission from the secondary $e^{\pm}$ pairs produced in p-p collisions. Our results indicate that the $\gamma$-rays detected with the Fermi LAT and H.E.S.S. are mainly from the p-p collisions of the protons in the shell interacting with the MC, whereas the radio emission are produced via synchrotron radiation of the electrons accelerated in the shell not interacting with the MC; moreover, the high-energy $\gamma$-rays obtained with Milagro at 35 TeV are possibly from p-p interactions of the protons accelerated in the shell interacting with the MC.

A MC can be illuminated by the particles escaped from a nearby SNR, and high-energy $\gamma$-rays can be produced when these particles diffuse into the cloud (Gabici et al. 2007; Fujita et al. 2009). For example, Torres et al. (2008) interpreted the source MAGIC J0616+225 as $\gamma$-ray emission from the particles escaped from the SNR IC 443 and diffusing into a MC located about 20 pc from the SNR. Moreover, the nonthermal radiative properties of the the open cluster Westerlund 2 and the old-age mixed-morphology SNR W28 can also be modeled as MCs illuminated by high-energy particles escaped from SNRs (Fujita et al. 2009). On the other hand, $\gamma$-rays can also be effectively produced from a shock wave colliding with a MC (e.g., Aharonian et al. 1994; Zhang & Fang 2008). $\gamma$-ray emission produced from a MC overtaken by a shock wave with a low Mach number has also been used to discuss the emission properties of the TeV sources, HESS J1745-303 (A) and HESS J1714-385 (Fang & Zhang 2008). In this paper, we model the SNR W51C as the MC around the remnant overtaken by part of the shell, and the other part of the shell expands into the relatively tenuous interstellar medium. The spectrum obtained with the Fermi LAT can be reproduced as $\gamma$-rays from p-p collisions of the protons in the shell with a low Mach number.

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