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High energy gamma rays from nebulae associated with extragalactic microquasars and ultra-luminous X-ray sources

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ABSTRACT

In the extragalactic sky, microquasars and ultra-luminous X-ray sources (ULXs) are known as energetic compact objects locating at off-nucleus positions in galaxies. Some of these objects are associated with expanding bubbles with a velocity of 80–250 km s^{-1}. We investigate the shock acceleration of particles in those expanding nebulae. The nebulae having fast expansion velocity $\gtrsim$ 120 km s^{-1} are able to accelerate cosmic rays up to ∼100 TeV. If 10% of the shock kinetic energy goes into particle acceleration, powerful nebulae such as the microquasar S26 in NGC 7793 would emit gamma rays up to several tens TeV with a photon index of ∼2. These nebulae will be good targets for future Cherenkov Telescope Array observations given its sensitivity and angular resolution. They would also contribute to ∼7% of the unresolved cosmic gamma-ray background radiation at ≥ 0.1 GeV. In contrast, particle acceleration in slowly expanding nebulae $\lesssim$ 120 km s^{-1} would be less efficient due to ion-neutral collisions and result in softer spectra at $\gtrsim$ 10 GeV.

1. Introduction

In the very high energy (VHE; $\gtrsim$ 50 GeV) gamma-ray sky, a few hundreds of objects have been detected by the Large Area Telescope (LAT) on board the *Fermi* gamma-ray telescope (*Fermi*) [7] and by the imaging atmospheric Cherenkov telescopes [see e.g. 84]. Further progress is anticipated in the near future by the Cherenkov Telescope Array (CTA) [8]. Its improved flux sensitivity and angular resolution will enable us to unveil new particle accelerators in the Universe.

In the extragalactic sky, various source classes have been considered for future CTA observations such as active galactic nuclei [76], gamma-ray bursts [38], star forming galaxies [3], and cluster of galaxies [3]. Here, the angular resolution of CTA will achieve $\lesssim$3 arcmin at $\gtrsim$1 TeV.[1] As angular sizes of nearby galaxies up to ∼10 Mpc is ∼10 arcmin, it would be possible to spatially resolve particle accelerators in those galaxies.

It would be difficult to detect supernova remnants or pulsar wind nebulae in extragalactic galaxies considering their luminosities ($L_\gamma \lesssim 10^{36}$ erg s^{-1}). Here, some galaxies are known to host more powerful compact objects such as microquasars and ultra-luminous X-ray sources (ULX) whose kinetic or radiative power is $\gtrsim 10^{39}$ erg s^{-1}. These objects are discovered at off-nucleus positions [27].

Microquasars are X-ray binary systems having relativistic bipolar outflows or jets whose kinetic power is greater than 10^{39} erg s^{-1} [63]. ULXs are also compact X-ray binary systems having X-ray luminosities greater than 10^{39} erg s^{-1} [27]. Although X-ray emission mechanisms from microquasars and ULXs are not fully understood yet,[2] some of them are known to be associated with expanding nebulae with a velocity of 80–250 km s^{-1} and a size of ∼200 pc [20,69]. Since the kinetic power of those nebulae is known to be comparable to or even greater than the radiative or jet kinetic power [20], the nebulae are good candidates as new

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[1] https://portal.cta-observatory.org/Pages/CTA-Performance.aspx.

[2] There are three distinct ideas widely considered to interpret high X-ray luminosities of ULXs, although there is no general agreement on their nature; sub- or trans-Eddington accretion onto intermediate mass black holes with a mass of $M_{BH} \gg 10M_\odot$ [e.g. 59], supercritical mass accretion onto stellar mass black holes [e.g. 30, 51], or accreting pulsars [e.g. 11].

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cosmic-ray acceleration sites and possibly they would emit gamma rays through hadronuclear interactions with ambient gases.

In this paper, we investigate the diffusive shock acceleration of particles in the expanding nebulae associated with extragalactic microquasars and ULXs. And, we estimate expected gamma-ray and neutrino signals from those nebulae. We further consider their contribution to the cosmic gamma-ray and neutrino background radiation and future detectability by CTA. Throughout this paper, we define $Q_x = Q/10^x$.

2. X-ray source embedded bubbles in the local universe

The size of the microquasar and ULX bubbles R_b is of an order of 200 pc and the expansion velocity of the bubbles is known to be $v_s = 80 - 250$ km s^{-1} [20,69]. Following the self-similar expansion law [47,86], the bubble size can be described as

$$R_b \approx 0.76(P_{\rm kin}/\mu m_p n_{\rm gas})^{1/5} t^{3/5} \sim 200 P_{\rm kin,40.5}^{0.2} n_{\rm gas,0.5}^{-0.2} t_{13.5}^{0.6} \ {\rm pc}, \quad (1)$$

where $P_{\rm kin}$ is the time-averaged kinetic power, $\mu = 0.61$ is the mean molecular weight, m_p is the proton mass, $n_{\rm gas}$ is the gas density, and t is the age of the system. Thus, the characteristic age of the bubble is

$$\tau = 3R_b/5v_s \sim 4.9 \times 10^5 R_{b,20.8} v_{s,7.1}^{-1} \ {\rm yr}. \quad (2)$$

This age is comparable to the expected ULX lifetime [e.g. 42,62]. Once we measure the bubble size and the expanding velocity, the time-averaged kinetic power of the bubble can be described as

$$P_{\rm kin} \approx 18 \mu m_p n_{\rm gas} R_b^2 v_s^3 \sim 3.6 \times 10^{40} R_{b,20.8}^2 v_{s,7.1}^3 n_{\rm gas,0.5} \ {\rm erg \ s^{-1}}. \quad (3)$$

The Mach number of the shock due to the expanding nebulae is estimated as

$$\mathcal{M} \approx v_s/(\gamma k_B T_u/\mu m_p)^{1/2} \sim 8.0 v_{s,7.1} T_{u,4}^{-1/2}, \quad (4)$$

where $\gamma = 5/3$ is the specific heat ratio, k_B is the Boltzmann constant, and T_u is the temperature of the upstream of the shock. $\mathcal{M}$ is larger than unity for the upstream cold gas component with $T_u < 10^4$ K. The dynamical timescale in which the shock dissipates is

$$t_{\rm dyn} \approx \frac{R_{\rm b}}{v_s} \sim 8.1 \times 10^5 R_{b,20.8} v_{s,7.1}^{-1} \ {\rm yr}. \quad (5)$$

The downstream temperature is estimated as

$$T_d \approx 2(\gamma - 1)\mu m_p v_s^2/k_B/(\gamma+1)^2 \sim 2.0 \times 10^5 v_{s,7.1}^2 \ {\rm K}. \quad (6)$$

Thus, radiative cooling plays an important role. For a solar metallicity interstellar medium (ISM) environment, the cooling time scale is given by [Eq. (34.4) of 24]

$$t_{\rm rad} \sim 1.4 \times 10^3 n_{\rm gas,0.5}^{-1} v_{s,7.1}^{17/5} \ {\rm yr}, \quad (7)$$

for $10^5 \lesssim T \lesssim 10^{7.3}$ K. If the metallicity is $0.1Z_\odot$, the time scale will become a factor of 3 longer. From Eqs. (5) and (7), the downstream plasma cools within dynamical timescale. In other words, these nebula shocks are radiative. UV photons from the radiative zone would significantly ionize the upstream ISM. At $v_s \gtrsim 120$ km s^{-1}, shock induced ionizing radiation is strong enough to completely ionize the upstream gas [36,56,74]. At the downstream, the temperature decreases and the density increases as the radiation cools the gas in the downstream. As the shock compression ratio $r = (\gamma+1)\mathcal{M}^2/[(\gamma-1)\mathcal{M}^2+2] \sim 4$ in our case, we assume the spectral index of 2 for simplicity in this paper.

Here, the magnetic field in the shock upstream can be described as

$$B_u = 1.7b\sqrt{n_{\rm gas,0.5}} \ \mu G, \quad (8)$$

where the dimensionless parameter b is $\sim$1 from Zeeman measurements of self-gravitating molecular clouds in the Galaxy [19].

The magnetic field in the downstream region will be amplified by compression as

$$B_d = \sqrt{\frac{1}{3} + \frac{2}{3} r^2} B_u \sim 5.7 n_{\rm gas,0.5}^{1/2} \ \mu G. \quad (9)$$

Here, if Alfvén-wave turbulence is fully generated, B_d can be amplified locally around the shocks [see e.g. 75,12,13,14]. In such cases, B_d would become as high as $B_d \approx (4\pi \xi_B f_{\rm ion} \mu n_{\rm gas} m_p v_s^2)^{1/2} \sim 74 \xi_{B,0}^{1/2} f_{\rm ion,0}^{1/2} n_{\rm gas,0.5}^{1/2} v_{s,7.1}$ μG, where ξ_B is the magnetic field amplification factor and $f_{\rm ion} \equiv n_n/(n_n + n_i)$ is the ionization fraction. n_n and n_i is the neutral particle density and the ionized particle density, respectively. However, we note that ion-neutral collisions suppress Alfvén wave [56,74] at $v_s \lesssim 120$ km s^{-1}. In this paper, we take Eq. (9) as the fiducial value for the downstream magnetic field.

The diffusive shock acceleration timescale can be written as

$$t_{\rm acc} \approx \frac{10}{3} \frac{\eta c r_g}{v_s^2} \sim 1.3 \times 10^6 Z^{-1} n_{\rm gas,0.5}^{-1/2} v_{s,7.1}^{-2} E_{\rm cr,14} \ {\rm yr}, \quad (10)$$

where $r_g = E_{\rm cr}/ZeB_d$ is the gyroradius and $\eta \geq 1$. For simplicity, we take $\eta = 1$ in this paper, i.e. the Bohm limit, since ULXs are known to be associated with star forming regions [e.g. 81,33,72] which would amplify the upstream turbulence. Such an efficient acceleration is possibly seen in a Galactic supernova remnant by assuming a simple diffusive shock acceleration model [83], although η can be different from unity by considering escape-limited acceleration [34,68] or stochastic acceleration [26].

The attainable maximum cosmic-ray energy is given by $t_{\rm acc} = t_{\rm dyn}$ (See Eqs. (5) and (10)):

$$E_{\rm cr,max} = \frac{3ZeB_d R_{\rm b} v_s}{10\eta c} \quad (11)$$

$$\sim 1.3 \times 10^{14} \eta_0 n_{\rm gas,0.5}^{1/2} v_{s,7.1} R_{\rm b,20.8} \ {\rm eV}, \quad (12)$$

TeV cosmic rays can be affordable from the extragalactic X-ray source nebulae. If the Alfvén-wave turbulence is fully generated, it will reach to $\sim$1 PeV.

The ionization state in the shock downstream strongly depends on its velocity [36,56,74]. If neutral particle exists, i.e. $v_s \lesssim 120$ km s^{-1}, ion-neutral collisions will lead damping of the magnetic turbulence in the shock precursor and those collisions will hamper acceleration of particles at the highest energies. The expected break energy can be estimated as [60, and references therein]

$$E_{\rm cr,br} \sim 1.9 \times 10^9 \ T_{u,4}^{-0.4} B_{u,-6}^2 (1 - f_{\rm ion})^{-1} f_{\rm ion}^{-1/2} n_{\rm gas,0.5}^{-3/2} \ {\rm eV}. \quad (13)$$

Thus, at $v_s \lesssim 120$ km s^{-1}, the particle spectrum will have a break at $\sim$10 GeV and become steeper by one power above the break. The ion fraction $f_{\rm ion}$ is estimated according to the steady-state model by Hollenbach and McKee [36].

Let us consider energy loss processes for cosmic rays. The energy loss timescale due to pp interactions can be estimated as

$$t_{pp} \approx \frac{1}{\kappa_{pp} 4 n_{\rm gas} \sigma_{pp} c} \sim 6.0 \times 10^6 n_{\rm gas,0.5}^{-1} \ {\rm yr}, \quad (14)$$

where the cross section $\sigma_{pp} \sim 3 \times 10^{-26}$ cm^2 for 10^{10-12} eV [46,48] and the inelasticity $\kappa_{pp} \approx 0.5$. The factor of 4 in front of $n_{\rm gas}$ is due to compression in the downstream. We note that the pp cross section depends logarithmically on the proton energy.

By considering the steady-state for simplicity, the hadronuclear interaction efficiency is estimated as

$$f_{\rm pp} = \frac{t_{\rm dyn}}{t_{\rm pp}} \sim 0.28 R_{\rm b,20.8} v_{s,7.1}^{-1} n_{\rm gas,0.5}. \quad (15)$$

In hadronuclear interactions, charged and neutral pions are generated at the ratio of $\pi^+ : \pi^0 \approx 2 : 1$. Gamma rays are produced by the decay of neutral pions as $\pi^0 \rightarrow 2\gamma$.