Gamma-ray sources like V407 Cygni in symbiotic stars

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ABSTRACT
Using a simple accelerating model and an assumption that γ-rays originate from p–p collisions for a π0 model, we investigate γ-ray sources like V407 Cygni in symbiotic stars. The upper limit of their occurrence rate in the Galaxy is between 0.5 and 5 yr−1, indicating that they may be important sources of high-energy γ-rays. The maximum energies of the accelerated protons mainly distribute around 10^{11} eV, and barely reach 10^{15} eV. The novae occurring in D-type SSs with ONe white dwarfs and long orbital periods are good candidates for γ-ray sources. Due to a short orbital period which results in a short acceleration duration, the nova occurring in symbiotic star RS Oph cannot produce γ-ray emission like that in V407 Cygni.

Key words: acceleration of particles – binaries: symbiotic – stars: individual: V407 Cygni – gamma-rays: general.

1 INTRODUCTION
Symbiotic stars (SSs) are usually interacting binaries, composed of a cool star, a hot component and a nebula. The hot component is usually a white dwarf (WD). The cool component is either a normal red giant (RG) in S-type SS or a Mira variable surrounded by an optically thick dust shell in D-type SS. Symbiotic novae are a small subclass of thermonuclear novae which occur on a WD surface fuelled by mass accreted from an RG. They can produce supersoft or soft X-ray emission in SSs (Mürsut, Wolff & Jordan 1997; Zhu et al. 2010).

V407 Cygni is a D-type SS consisting of a Mira-type pulsating RG. Recently, Abdou et al. (2010) reported the Fermi Large Area Telescope detection of variable γ-ray emission (0.1–10 GeV) from the nova of SS V407 Cygni. They explained that the γ-ray spectrum originates from proton–proton (p–p) interaction by π0 model,1 but inverse Compton scattering (see Blumenthal & Gould 1970 for an exclusive review) of infrared photons from the RG by electrons cannot be ruled out. The above two mechanisms producing γ-rays need high-energy protons or electrons. Cosmic rays with high energies are thought to originate from supernova remnants (SNRs). In order to have an efficient acceleration mechanism the theory of diffusive shock acceleration has been developed (see a recent review from Malkov & Drury 2001). Diffusive shock acceleration applies only for particles with a Larmor radius larger than the typical shock thickness. If electrons and protons are in equilibrium in the shock, the Larmor radius of electron is a factor (m_e/m_p)^{1/2} smaller than that of proton, where m_e and m_p are masses of an electron and a proton, respectively. Only electrons which are already relativistic can cross the shock and start accelerating. Therefore, protons are accelerated more easily than electrons under the mechanism of diffusive shock acceleration.

In this Letter, we investigate the likely possibility of the symbiotic novae producing γ-rays, then assume that γ-rays originate from p–p collisions for a π0 model and investigate the γ-ray sources in SSs.

2 ACCELERATION MODEL
In general, the theory of diffusive shock acceleration is used for SNRs to explain the emission of cosmic rays with high energy. In this work the acceleration model used for the symbiotic nova like V407 Cygni is similar to that used for SNRs. There is usually a low particle density circumstellar medium (CSM) around SNRs. However, a symbiotic nova like V407 Cygni is usually embedded in a dense CSM which is mainly formed from stellar winds lost by the RG. This difference makes it possible to efficiently accelerate protons in symbiotic novae.

According to the theory of diffusive shock acceleration for SNRs, the maximum attainable energy for cosmic rays is determined by the size of the accelerator, the magnetic field of the CSM and the energy losses resulting from adiabatic and synchrotron processes. The size depends on the explosion evolution of SNR. According
The nova occurring in SSs are surrounded by the dense stellar winds from the RGs. They offer an environment for high efficient particle acceleration. Therefore, they may be important sources of high-energy $\gamma$-rays in the Galaxy.

3 SYMBIOTIC STARS

In general, SSs are the detached interacting binaries in which the WDs accrete the matter of the RGs via stellar winds. By a population synthesis method, Lü, Yungelson & Han (2006) carried out a detailed investigation of SSs. They found that the occurrence rate of the novae in SSs is greatly affected by common-envelope evolution and the stellar wind velocity $V_w$ of the RG. Following Lü et al. (2006) and Zhu et al. (2010), for common-envelope evolution in different simulations we use $\alpha = 0.5$ in $\alpha$-algorithm and $\gamma = 1.75$ in $\gamma$-algorithm, respectively, for the stellar wind, $V_n = (1/2)\nu_{esc}$ where $\nu_{esc}$ is the escape velocity and $V_n$ is determined by the relation between the mass-loss rates and the terminal wind velocities fitted by Winters et al. (2003) as

$$\log_{10}(M/M_\odot \text{ yr}^{-1}) = -7.40 + \frac{4}{3} \log_{10}(V_n/km \text{ s}^{-1}).$$

In this work we consider three cases with different input parameters:

(i) in case 1, $\alpha = 0.5$ and $V_n = (1/2)\nu_{esc};$

(ii) in case 2, $\gamma = 1.75$ and $V_n = (1/2)\nu_{esc};$

(iii) in case 3, $\alpha = 0.5$ and $V_n$ taken as equation (5).

Using the model of SSs and grid for novae in Yaron et al. (2005), we can estimate $E_{\gamma \text{max}}$ in which $\theta = 0$ and $\eta = 0.01$ for every nova. According to Kamae et al. (2006), $p$–$p$ interaction can occur when the energy of proton is higher than $10^7$ eV, which results in $\gamma$-ray emission. Therefore, we assume that the novae in SSs are $\gamma$-ray sources if the $E_{\gamma \text{max}}$ in equation (1) is higher than $10^7$ eV.

4 RESULTS

Using a population synthesis method described in Lü et al. (2006, 2008), we model $10^6$ binary systems which gives a statistical error for our Monte Carlo simulation lower than 5 per cent for the symbiotic nova. In order to estimate the occurrence rate of $\gamma$-ray sources like V407 Cygni, we assume that one binary with primary mass more than 0.8 $M_\odot$ is formed annually in the Galaxy. We do not consider the energy losses of the accelerated protons via adiabatic and synchrotron processes. Therefore, we overestimate the maximum energy of the proton and the occurrence rate of $\gamma$-ray sources in this work.

We select symbiotic novae as $\gamma$-ray sources if $E_{\gamma \text{max}}$ of the accelerated protons is larger than $10^7$ eV. Our model shows that the upper limits of the occurrence rates of $\gamma$-ray sources like V407 Cygni in SSs are 0.5 yr$^{-1}$ in case 1, 2.0 yr$^{-1}$ in case 2 and 5.0 yr$^{-1}$ in case 3, respectively. Compared with the results in Lü et al. (2006), about 15 per cent of the novae in SSs for cases 1 and 2 can produce $\gamma$-ray emission, and it is 40 per cent in case 3 because the wind velocity in equation (5) is favourable for a strong nuclear outburst. If the Galactic cosmic rays originate from the supernova whose occurrence in the Galaxy is $\sim 0.01$ yr$^{-1}$, we suggest that symbiotic nova like V407 Cygni may be another important source of high-energy $\gamma$-rays. However, the contribution of the symbiotic noave to total cosmic rays cannot be known until the spectral energy distribution of $\gamma$-rays from the novae is calculated, which will be carried out in further work.

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Fig. 1 shows the distribution of the WD's masses versus orbital periods for SSs as γ-ray sources in cases 1, 2 and 3. The gradations of gray-scale correspond to the regions where the number density of systems is, respectively, within 1–2, 2–4, 4–6, 6–8 and 8–10, and blank regions do not contain any star.

Evidence for gamma-ray emission like that in V407 Cygni in the 2006 outburst. The orbital period of V407 Cygni is ~40 times that of RS Oph, which means that the density of CSM around the WD in the latter is higher than 100 times that in the former if $M_t/V_w$ is comparable in the two binaries. Therefore, the duration of the diffusive shock acceleration in the 2006 outburst of RS Oph, $t_{ST}$, is too short so that protons and electrons cannot be accelerated enough to produce γ-ray emission.

Fig. 2 gives the distribution of $E_{\gamma\max}^p$ versus $V_{\gamma\max}$, where $E_{\gamma\max}^p$ is at ~$10^{11}$ eV and $E_{\gamma\max}^p$ hardly reaches ~$3 \times 10^{15}$ eV which is the knee of the cosmic ray spectra. If the γ-ray energy originating from p–p interaction is comparable to $E_{\gamma\max}^p$, they should be in the low-frequency part of high-energy cosmic rays. These nuclear outbursts are very strong so that the ejecta have high velocity. As Fig. 2 shows, $V_{\gamma\max}$ in the symbiotic novae is ~several $\times 10^3$ km s$^{-1}$. According to the calculations of Yaron et al. (2005), in these strong nuclear outbursts most of the accreted matter is expelled and in some cases even an erosion of the WD occurs. Therefore, the massive WDs in γ-ray sources do not explode as supernovae.

Fig. 3 shows the distribution of the duration of Sedov–Taylor phase $t_{ST}$ versus the magnetic field of the stellar wind from RSs. The peaks of the magnetic field distribution are ~$10^{-2}$ G in cases 1 and 2, and it is ~$10^{-3}$ G in case 3 because a high mass-loss rate results in high $V_w$ (see equation 5). The magnetic fields of the stellar winds around the novae in SSs are $10^3$ times higher than those of CSM around the SNRs. The peak of $t_{ST}$ is at ~3 d in cases 1 and 2, while it is ~$10^2$ d in case 3 due to a high $V_w$ which results in the low

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**Figure 1.** Gray-scale maps of WD's masses versus orbital periods for SSs as γ-ray sources in cases 1, 2 and 3. The gradations of gray-scale correspond to the regions where the number density of systems is, respectively, within 1–2, 2–4, 4–6, 6–8 and 8–10, and blank regions do not contain any star.

**Figure 2.** Similar to Fig. 1, but for the maximum energy $E_{\gamma\max}^p$ of the protons accelerated versus the shock velocity $V_{\gamma\max}$. **Figure 3.** Distribution of the duration of Sedov–Taylor phase $t_{ST}$ versus the magnetic field of the stellar wind from RSs.
5 CONCLUSIONS

In this Letter, we use a toy model to investigate the $\gamma$-ray sources which originate from $p$–$p$ collisions in the novae of SSs. The symbiotic novae occurring on the surface of accreting WDs are surrounded by dense stellar winds from the RGs. They offer an environment for highly efficient particle acceleration. We estimate that the upper limit of the occurrence rate of $\gamma$-ray sources in SSs in the Galaxy is between 0.5 and 5 yr$^{-1}$. Therefore, they may be important sources of high-energy $\gamma$-rays. The maximum energies of the accelerated protons mainly distribute around $10^{11}$ eV, and barely reaches $10^{15}$ eV. If the $\gamma$-ray energy originating from $p$–$p$ interaction is comparable to $E_p^{\text{max}}$, they should be in the low-frequency part of high-energy cosmic rays. In SSs as $\gamma$-ray sources, majority of WDs are ONe WDs and have masses larger than $1.3 M_\odot$, and most of the RGs have dust shells. The novae occurring in D-type SSs with ONe WDs are good candidates as $\gamma$-ray sources. Due to the short orbital period, the nova occurring in RS Oph hardly produces $\gamma$-ray emission like that in V407 Cygni.

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REFERENCES

Abdo A. A. et al., 2010, Sci, 329, 817
Blumenthal G. R., Gould R. J., 1970, Rev. Modern Phys., 42, 237
Bode M. F., Kahn F. D., 1985, MNRAS, 217, 205
Bode M. F. et al., 2006, ApJ, 652, 629
Ferrariott A. S., Gail H., 2006, A&A, 447, 553
Gail H., Sedlmayr E., 1986, A&A, 161, 201
Gail H., Sedlmayr E., 1999, A&A, 347, 594
Hirose K., 2006, IAU Circ., 8671
Kamae T., Karlsson N., Mizuno T., Abe T., Koi T., 2006, ApJ, 647, 692
Kirk J. G., 1994, in Benz A. O., Courvoisier T. J. - L., eds, Saas-Fee Advanced Course 24: Plasma Astrophysics. Springer, Berlin, p. 225
Lü G., Yungelson L., Han Z., 2006, MNRAS, 372, 1389
Lü G., Zhu C., Han Z., Wang Z., 2008, ApJ, 683, 990
Malkov M. A., Drury L., 2001, Rep. Progress Phys., 64, 429
McKee C. F., Truelove J. K., 1995, Phys. Rep., 256, 157
Munari U., Margoni R., Stagni R., 1990, MNRAS, 242, 653
Müser U., Wolf B., Jordan S., 1997, A&A, 319, 201
Nelson T., Orio M., Cassinelli J. P., Still M., Leibowitz E., Mucciarelli P., 2008, ApJ, 673, 1067
Schure K. M., Achterberg A., Keppens R., Vink J., 2010, MNRAS, 406, 2636
Winters J. M., Le Bertre T., Jeong K. S., Nyman L., Eichelin N., 2003, A&A, 409, 715
Yaron O., Pratikni D., Shara M. M., Kovetz A., 2005, ApJ, 623, 398
Zhu C., Lü G., Wang Z., Zhang J., 2010, New Astron., 15, 144

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