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# A NEW CLASS OF GALACTIC DISCRETE $\gamma$-RAY SOURCES: CHAOTIC WINDS OF MASSIVE STARS

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## ABSTRACT

We propose a new class of galactic discrete $\gamma$-ray sources, the chaotic, high mass-loss-rate winds from luminous early-type stars. Early-type stellar winds are highly unstable due to intrinsic line-driven instabilities, and so are permeated by numerous strong shocks. These shocks can accelerate a small fraction of thermal electrons and ions to relativistic energies via the first-order Fermi mechanism. A power-law-like photon spectrum extending from keV to above 10 MeV energies is produced by inverse Compton scattering of the extremely abundant stellar UV photons by the relativistic electrons. In addition, a typical $\pi^0$-decay $\gamma$-ray spectrum is generated by proton-ion interactions in the densest part of the winds.

## 1. INTRODUCTION

Until recently the theoretical and observational studies of discrete cosmic $\gamma$-ray sources were focused on those where a large fraction of their total energy output is believed to be in $\gamma$-rays (*e.g.*, neutron stars, supernovae, or candidates for black holes), because in general they are also the brightest. The capability of the *Compton Gamma Ray Observatory (CGRO)* to detect much fainter sources than before marks the beginning of a new era. We can now not only study the luminous $\gamma$-ray sources at larger distances, but we can also explore the intrinsically weak sources whose $\gamma$-ray radiation may represent only a small fraction of their total energy output. As we have shown in recent papers (Chen & White 1991c; Chen & White 1992a), the chaotic winds of massive stars may well possibly be such a new class of Galactic discrete $\gamma$-ray sources.

Many authors have pointed out (White 1985; Pollock 1987a; Montmerle 1990) that $\gamma$-rays may be produced in the entire circumstellar atmosphere of the hot stars by relativistic particles (electrons and ions), which are accelerated from the thermal population via the first-order Fermi mechanism by shocks embedded in the winds. Since these stellar winds generally have simple spherical geometries and well measured stellar/wind parameters, they provide a particularly clean astrophysical laboratory to study shocks, Fermi particle acceleration and other high energy physical processes which are in general confused by complex geometries, unknown physical parameters and/or other complications in neutron stars, accreting binaries or AGNs.

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In this paper, we draw an overall picture of the $\gamma$-ray production by chaotic stellar winds. Its specific application to Cyg OB2 stellar association is addressed elsewhere (Chen & White, this volume).

## 2. CHAOTIC WINDS

Early-type stars (O, early B and Wolf-Rayet stars) occupy the upper-left corner of the Hertzsprung-Russell diagram. They are all very hot ($T_{eff} > 20,000$ K), massive ($M > 20\,M_{\odot}$, progenitor mass for WR stars) and luminous ($L_{bol} > 10^5 - 10^6\,L_{\odot}$). While the enormous radiation of a massive star provides abundant ionizing UV photons for the surrounding HII region, its extremely large radiation pressure drives the outer atmosphere outwards to form a strong stellar wind. The typical mass-loss rate of a massive star ranges from $10^{-6} - 10^{-4}\,M_{\odot}\,\mathrm{yr}^{-1}$, and the typical wind terminal velocity is usually greater than $10^3\,\mathrm{km\,s}^{-1}$ (Cassinelli 1979). Such strong stellar winds ($L_w \geq 10^{37}\,\mathrm{ergs\,s}^{-1}$) are one of the major sources of mass and energy input into the interstellar medium (Abbott 1982).

The radiation force in the early-type stellar winds accelerates the mass outflow through scattering and absorption by thousands of spectral lines of the heavy elements rather than just electron scattering (Castor, Abbott & Klein 1975; Pauldrach, Puls & Kudritzki 1986). The progressive Doppler shifting of the line opacity into the unattenuated photospheric radiation field can result in a very rapid acceleration to the terminal wind velocity, $V(r) = V_{\infty}(1 - R_*/r)^{\beta}$ where $\beta \sim 1$.

Since the line-driven force depends strongly on the velocity gradient, however, it also introduces severe intrinsic instabilities to the wind flow (Owocki & Rybicki 1984). If a gas parcel in a line center moves a little faster than the surrounding gas, it moves to the blue wing where it sees a less attenuated radiation field. It consequently is subjected to greater radiative acceleration and moves even faster. Recent numerical simulations (Owocki, Castor & Rybicki 1988) show that such an instability can grow exponentially into a nonlinear phase with strong multiple shocks in the winds; the resulting wind velocity structure agrees well with Lucy's (1982) speculations. However, Lucy's theory predicts about a few percent or so of the wind kinetic power will go into shocks, $L_s \geq 10^{35}\,\mathrm{ergs\,s}^{-1}$, but Owocki *et al.*'s simulations generate considerably less power in shocks.

Due to the large column density of the winds, the post-shock gas cools very quickly. The thickness of the post-shock cooling region is only a tiny fraction of the typical length scale in the winds, so the shocks are usually isothermal (Lucy 1982; Krolik & Raymond 1985; Owocki, Castor & Rybicki 1988; Chen & White 1991a).

The existence of strong shocks permeating in winds has long been used to explain the soft X-ray emission from early-type stars (Lucy & White 1980; Lucy 1982) observed by the *Einstein Observatory* in early 1980's (*e.g.*, Rosner, Golub & Vaiana 1985). The small amount of absorption observed at the low energy band of the IPC favors the shock interpretation over other alternatives like the corona model (Cassinelli & Olson 1979) in which soft X-rays from a hot corona of a few million degrees located deep at the base of the winds would have suffered severe photoelectric attenuation. The once-in-a-lifetime observation of Orion OB supergiants by the SSS on *Einstein* (Cassinelli & Swank 1983) reveals a hard X-ray component above 2 keV which places a more severe constraint on the corona model: to explain this one needs an even-hotter corona of a few $10^7$ K superimposed on the cooler one. It seems not conceivable to build such a two-component corona above the fully radiative upper photosphere of early-type stars.

On the other hand, if we adopt the shock model, the hard X-ray excess can be naturally explained by the inverse-Compton scattering of the stellar UV photons by relativistic electrons accelerated by the shocks in the winds (Chen & White 1991a). The existence of relativistic electrons in the hot stellar winds gains its primary support from radio observations: a synchrotron radiation model (White 1985) can account for the nonthermal radio emission observed from about 25% of early-type stars (Abbott *et al.* 1986; Bieging, Abbott & Churchwell 1989). These successes have prompted many authors to speculate that the relativistic particles accelerated by shocks in the winds may provide a natural platform for a unified theory of non-thermal emissions from hot stars (White 1985; Pollock 1987a; Montmerle 1990; Chen & White 1991b).

## 3. PARTICLE ACCELERATION

Particle acceleration at astrophysical shock fronts via the first-order Fermi mechanism is believed to be responsible for the production of relativistic particles (cosmic rays) in a variety of astrophysical circumstances (see recent reviews by Blandford & Eichler 1987 and Jones & Ellison 1991). For strong steady-state shocks, results from a simple test particle method (Bell 1987) agree well with that from other more advanced (but more complicated) approaches (Blandford & Eichler 1987; Jones & Ellison 1991).

The accelerated particle spectral index $\alpha$ depends only on the shock velocity jump $\chi$, $\alpha = (\chi + 2)/(\chi - 1)$. An isothermal shock with large velocity jump produces a much flatter particle spectrum than an adiabatic shock. However, if the diffusion length of particles is a function of energy, less energetic particles may travel only across the adiabatic sub-shock front. In this case the particle spectrum is concave: it is steep at low energies and flattens towards higher energies (Chen & White 1991a).

In stellar winds, the electron spectrum is further modified (Chen & White 1991a) by the severe inverse Compton losses even at fairly large radii (Pollock 1987a; Chen & White 1991a). While the competition between the acceleration and radiative cooling completely determines the electron high energy cutoff, it also tends to encourage electrons to pile up just below the cutoff. The electron spectrum near the shock front in winds exhibits a high energy hump (Webb, Drury & Biermann 1984; Fritz 1989) that develops into a sharp spike farther away from the shock (Fritz 1989; Chen & White 1991a).

We do not know yet how the post-shock pressure is distributed between the thermal and nonthermal components (Blandford & Eichler 1987; Jones & Ellison 1991). A simple phenomenological approach to this problem is to assign a fixed post-shock pressure ratio of the nonthermal particles to the thermal gas and then compare the model results with observations. Comparison of the thermal X-ray spectra of Orion stars observed by SSS (Cassinelli & Swank 1983) with the predictions from Lucy's model reveals this ratio to be $\sim 20\%$ (Chen & White 1991a), a value that agrees well with direct measurements at the

Earth's bow shock (Ellison, Möbius & Paschmann 1990).

The electrons are harder to accelerate (Blandford & Eichler 1987; Jones & Ellison 1991) and in general have softer spectra (Chen & White 1991a). Fitting the hard X-ray component with our inverse Compton model suggests a self-consistent post-shock electron pressure ratio of about 5% (Chen & White 1991a; Chen & White 1991c). These values are used for our calculations for all stars and the expected uncertainty is less than a factor of a few.

The multiple shock structure in the massive stellar winds raises another interesting theoretical challenge: to find an effective method to deal with multiple acceleration of particles by shocks. We have developed a powerful analytical formula for this problem (Chen & White 1992b) based on a revised version of Bell's (1978) single particle method which includes the inverse Compton cooling effects (Chen & White 1991a). Our results generally agree well with White's (1985) simpler analysis: multiple acceleration flattens the electron spectrum.

## 4. $\gamma$-RAY PRODUCTION

Both relativistic ions and electrons may potentially produce $\gamma$-ray radiation in winds, though through different emission mechanisms and in different energy ranges. Pollock (1987a) suggests that $\gamma$-rays up to GeV energies from massive stellar winds may come from bremsstrahlung radiation of the relativistic electrons. But our study shows that for electrons inverse Compton cooling is the most important energy loss mechanism (Chen & White 1991a) and so almost all the energies pumped into suprathermal electrons is radiated away via inverse Compton scattering. The up-scattered photon spectrum is a quasi-power-law from keV to $\geq 10$ MeV energies (Chen & White 1991c).

The relativistic ions in winds produce $\gamma$-rays through decays of neutral pions which are generated by the ion-ion collisions with thermal ions in the winds (White 1985). A power-law spectrum of nonthermal ions produces a typical $\pi^0$-decay $\gamma$-ray hump peaking at $\sim 67$ MeV (*e.g.*, Trombka & Fichtel 1983).

The $\gamma$-ray luminosity of the inverse-Compton and $\pi^0$-decay components can be roughly estimated from the wind energy budget argument (Chen & White 1991c). The total energy going into nonthermal ions is $\geq 10\%$ of the shock's kinetic power, *i.e.*, $L_i \geq 10^{34}\,\mathrm{ergs\,s^{-1}}$, and the energy going into nonthermal electrons is about an order of magnitude less, $L_e \geq 10^{33}\,\mathrm{ergs\,s^{-1}}$. The electron-generated inverse Compton $\gamma$-ray luminosity is roughly of the same order of the total electron power, $L_{\gamma,e} \sim 10^{33}\,\mathrm{ergs\,s^{-1}}$; but the ion-generated $\pi^0$-decay $\gamma$-ray luminosity is $< 10\%$ of the total ion power, *i.e.*, $L_{\gamma,i} \sim 10^{33}\,\mathrm{ergs\,s^{-1}}$, since the ion-ion interaction optical depth in the winds is usually $< 0.1$.

The $\pi^0$-decay $\gamma$-ray luminosity is expected to be much larger from high mass-loss-rate winds, including many Wolf-Rayet stars and some of the early O stars, since it depends on the the densities of both thermal and nonthermal ions (which scale roughly the same way), $L_{\gamma,i} \propto \dot{M}^2/(R_* V_\infty{}^2)$. The driving mechanism of Wolf-Rayet winds, however, is still a subject of debate which introduces large uncertainties in their expected $\gamma$-ray fluxes (Chen & White 1992a). On the other hand, the inverse-Compton $\gamma$-ray luminosity depends also on the stellar photospheric luminosity, $L_{\gamma,e} \propto \dot{M}\, L_{bol}/(R_* V_\infty)$. So in general high luminosity stars may have higher flux at sub-MeV energies and high mass-loss-rate winds will be brighter in GeV energies.

The stellar magnetic fields have a profound effects on both the inverse-Compton and $\pi^0$-decay $\gamma$-ray fluxes. This is simply because the local field strength defines the particle diffusion length scale near the shock front (White 1985). A larger field means a smaller mean free path for both ions and electrons, which then gives a greater high energy cutoff for the particle spectra. Since we have fixed the total energy share of the nonthermal particles in the post-shock region, a larger energy span leads to a lower number density of the particles. This in turn produces a more energetic photon spectrum but less flux at peak energies. In our models we choose low field strength for O stars ($\sim$ 1 Gauss) and higher values ($\geq$ 100 Gauss) for Wolf-Rayet stars based on earlier estimates from radio and X-ray observations (White 1985; Abbott *et al.* 1986; Pollock 1987a; Bieging, Abbott & Churchwell 1989; Chen & White 1991a; Chen & White 1992a).

The detectability of $\gamma$-ray emission from early-type stellar winds by various *CGRO* instruments depends sensitively on the spectral shape and relative intensity of the two components of ions and electrons for a given star. Our calculations show that $\gamma$-ray flux from some nearby ($\leq$ 2 kpc) massive stars are marginally detectable by both OSSE and EGRET (Chen & White 1991c; Chen & White 1992a). Given the moderate spatial resolution of *CGRO*, the combined $\gamma$-ray flux from a dense stellar association can have a much better chance of being detected. We will address this in more detail in a companion paper (Chen & White, this volume).

## 5. OUTLOOK

Though the idea of potential $\gamma$-ray emission from early-type stellar winds is not new (White 1985; Pollock 1987a; Montmerle 1990), our recent studies have put these ideas on a firm physical foundation, and we have constructed a quantitative model that can be compared directly with observations. Exploration by *CGRO* will not only reveal/confirm the violent nature of these otherwise "normal" stars but also will help improve our understanding of Fermi acceleration of particles by shocks. The knowledge we gain here can be applied to a variety of astrophysical circumstances.

Our study of stellar wind $\gamma$-ray emission is an important part of our much larger effort to draw a unified picture of nonthermal emissions from chaotic massive stellar winds (Pollock 1987a; Montmerle 1990; Chen & White 1991b). Figure 1 shows such a broadband spectrum we envision for a luminous massive star and its circumstellar wind. Notice that the dashed lines represents the flux predicted from our theoretical calculations. Observations in all the wavelengths will help to solidify this picture, and we expect pioneering observations by *CGRO* to play a very important role.

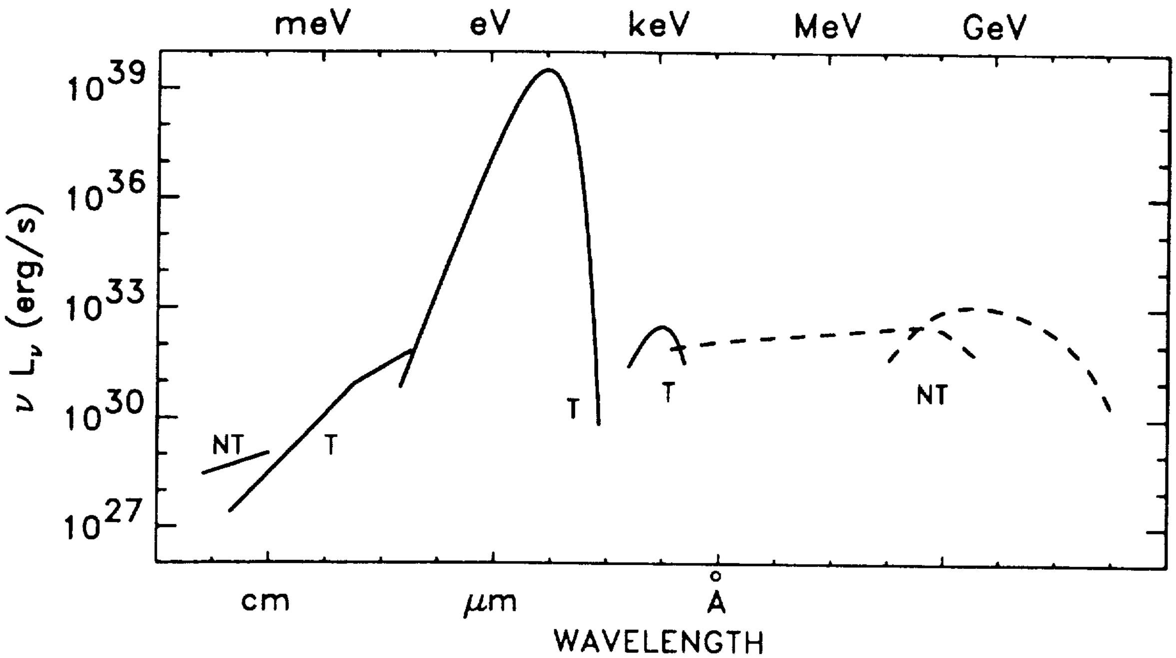


**Figure 1.** The broad band spectrum from radio to $\gamma$-ray for a typical early-type massive star. Spectra marked NT are the nonthermal components, marked T are the thermal components. Thermal radio-IR is the free-free radiation of the hot wind. Thermal X-ray emission is from the shocks in the wind. All the nonthermal radio, X-ray and $\gamma$-ray emission are produced by relativistic particles accelerated by the shocks. We see that $\gamma$-rays dominate the nonthermal emission.

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