Post-Periastron Gamma Ray Flare from PSR B1259−63/LS 2883 as a Result of Comptonization of the Cold Pulsar Wind

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ABSTRACT

The recent detection of gamma rays with the *Fermi* Large Area Telescope (LAT) from the binary system PSR B1259−63/LS2883 provides unique information about the pulsar wind. Although the nature of the weak gamma-ray signal detected at the periastron passage remains uncertain, the reported fluxes allow robust constraints on the Lorentz factor Γ_0 of the pulsar wind. Unless the latter is strongly anisotropic, the range of Γ_0 between 10^4 and 3×10^5 is excluded by the *Fermi* data. Moreover, we argue that the "surprise" gamma ray flare detected by *Fermi* after several weeks of the periastron passage can be explained by inverse Compton (IC) emission of the cold pulsar wind with $\Gamma_0 \approx 10^4$. The combination of two independent effects, both linked to the circumstellar disk, is a principal element in the proposed scenario. The first is related to radiation of the shocked stellar disk which in the close vicinity of the pulsar can provide a dense photon target for the IC scattering. The second effect is related to the strong impact of the surrounding medium ram pressure on location of the termination shock. Inside the disk, the pulsar termination shock stands close to the pulsar; consequently the "early" termination results in suppression of gamma-ray luminosity of the wind. When the pulsar escapes the disk, a fast transformation of the termination shock occurs leading to a significant increase of the pulsar wind zone towards the observer and, consequently to an enhancement of the gamma ray production rate.

Subject headings: binaries: close — gamma rays: stars — pulsars: individual (PSR B1259−63)

1. Introduction

The pulsars may emit potentially detectable gamma ray emission caused by Comptonization of low-frequency radiation by electrons of the cold ultrarelativistic pulsar wind (Bogovalov & Aharonian 2000). While in the case of an isolated pulsar this radiation component generaly is weak, in binary systems the pulsar wind IC emission is significantly enhanced due to the presence of dense target photon field provided by the optical companion (Ball & Kirk 2000; Ball & Dodd 2001; Khangulyan et al. 2007, 2011). The flux level of this emission component depends on several key model parameters: (i) the pulsar wind bulk Lorentz factor and the level of its anisotropy; (ii) the local density and energy distribution of target radiation fields; (iii) the so-called η parameter, the ratio of ram pressures of the pulsar and stellar winds (Bogovalov et al. 2008). In the specific case of PSR B1259−63/LS2883, where a 47.7 ms pulsar orbits a luminous star in a very eccentric orbit (eccentricity $e = 0.87$, period $P_{\rm orb} = 1237$ d, semi-major axis $a_2 = 7.2\,{\rm AU}$; see Johnston et al. (1992); Negueruela et al. (2011) and and references therein), the gamma ray signal of the unshocked wind should be strong enough to be detected by *Fermi* LAT at the periastron passage (Khangulyan et al. 2011).

The recent observations of PSR B1259−63/LS2883 with *Fermi* LAT revealed a rather complex behavior of the system in GeV gamma rays (Abdo et al. 2011; Tam et al. 2011). Close to the periastron passage, the source has been detected with a tiny energy flux $6 \times 10^{-11}{\rm erg\,cm^{-2}\,s^{-1}}$. A month after the periastron passage a spectacular flare has been detected. It lasted approximately two weeks with an enhanced flux above 100 MeV at the level of $3 \times 10^{-10}{\rm erg\,cm^{-2}\,s^{-1}}$ (Abdo et al. 2011; Tam et al. 2011). The flare has been characterized by a very sharp increase and by a rather smooth decay over approximately 2 week. Here we argue that the GeV signal during the flare can be explained by the inverse Compton emission of the cold ultrarelativistic pulsar wind.

It is important to note, that due to the presence of the circumstellar disk in the system, a rather sudden change of the gamma ray flux may occur at the pulsar entrance (exit) to (from) the stellar disk. As indicated by de Jager (2010) in different occasions, the disk itself can be an important source of target photons for Compton scattering of electrons. van Soelen & Meintjes (2011) have studied the impact of the radiation of the disk on the formation of IC gamma rays, and arrived to the conclusion that the GeV gamma ray production rate can be increased by a factor of 2. In fact, the impact of the disk emission may be significantly stronger. Though the disk luminosity is below the luminosity of the star, the regions of the disk close to the pulsar maybe significantly heated due to the pulsar–disk interaction. Thus, locally the energy density of the disk emission may strongly dominate over the optical emission of the star. This is especially important for IC radiation of the unshocked wind, given that in this case the interaction does not proceed in the saturation regime. Thus, at certain orbital phases, the flux level may be significantly enhanced due to the interaction with the disk photons.

2. Unshocked Wind Emission

In Figure 1 we show the spectral energy distribution (SED) of IC radiation of the pulsar wind averaged over 53 days close to periastron passage (namely, for the interval from -35 to 18 days from the periastron). The calculations are performed for different values of the η parameter: $\eta = 1$ (solid lines); $\eta = 0.05$ (dotted lines); $\eta = 1.1 \times 10^{-3}$ (dashed line). These value correspond to the following interaction regimes: $\eta = 1$ – the upper limit; $\eta = 0.05$ – for the interaction with the stellar wind; $\eta = 1.1 \times 10^{-3}$ – for the interaction with the circumstellar disk (see Khangulyan et al. 2011, for details). The curves presented in Figure 1 correspond to the initial Lorentz factors of the pulsar wind $\Gamma_0 = 10^4, 3\times10^4, 10^5$ and 3×10^5. The comparison of calculations with the *Fermi* data show that the IC radiation of the unshocked wind can easily achieve the level of reported fluxes. Quite remarkably, these fluxes are also rather close to theoretical predictions performed for radiation of the shocked wind (see e.g. Figs. 7 and 13 in Khangulyan et al. 2007). Unfortunately the marginal gamma ray signal obtained during the periastron passage does not allow a quantitative analysis which would give preference to the radiation component associated with the wind before or after its termination. On the other hand, these fluxes can be treated as upper limits, which allow us to obtain quite meaningful constraints on the Lorentz factor of the pulsar wind. Namely, as it follows from Figure 1 the interval of the pulsar wind Lorentz factor $\Gamma_0 \sim 10^4 - 3 \times 10^5$ is robustly excluded by the results of the *Fermi* collaboration (Abdo et al. 2011). Although this constraint can be formally relaxed in the case of strong anisotropy of the energy flux in the pulsar wind or in the case of very large ram pressure of the stellar wind (i.e. low values of η), but in practice this constraint seems to be a quite solid.

The gamma ray signal from the pulsar wind associated with the target photons of the companion star has a rather smooth orbital phase dependence (Khangulyan et al. 2011). In contrary, the circumstellar disk can introduce quite sharp temporal features (Khangulyan et al. 2011). The properties of the stellar disk and its possible impact on the non-thermal activity of the system presently are a subject of debate. In particular, the recent numerical studies by Okazaki et al. (2011) revealed that the circumstellar disk itself may be significantly disrupted by the pulsar wind, and basically to be truncated at a radius significantly smaller than the pulsar orbit. If true, this should reduce the impact of the disk to the gamma radiation. Nevertheless, here we assume that the circumstellar disk is present in the system, and that it extends to a relatively large distances. This assumption is supported by eclipses of the pulsed radio emission, which occur at epochs close to the periastron passage. In particular, the pulsar eclipses, occurred between -16 and 18 days to periastron passage in 2004 (Connors et al. 2002), and between -16 and 15 days to periastron passage in 2010 (Abdo et al. 2011), suggest that the disk should extend at least up to 3×10^{13} cm from the star.

The disk may affect the gamma ray signal of the pulsar wind in three different ways:

(i) because of the higher ram pressure inside the disk, a dramatic change of the η parameter is expected when the pulsar enters or leaves the disk. The change of the η parameter implies a change of the length of the unshocked wind, and therefore strong decrease of the IC gamma ray flux;

(ii) because of the additional target photons related to the disk, one may expect enhanced IC gamma ray production rate closer to the disk;

(iii) since the stellar disk is expected to be Keplerian, the flow velocity is oriented azimuthaly. Thus, the orientation of the termination shock in the case of the pulsar–disk interaction changes when the pulsar enters/leaves the disk. Namely, the axis of symmetry is orientated along the disk–pulsar relative velocity (but not along the line connecting the stars).

The effects (i) and (ii) have impacts on gamma ray fluxes in opposite directions, and therefore cannot be treated separately. Namely, the increase of the η parameter caused by the disk high ram pressure, shrinks the interaction region, thus leading to suppression of the gamma ray flux. On the other hand, the additional disk emitted photons increase the electron interaction rate and thus provides a higher gamma ray flux. Obviously, the overall effect depends on the circumstellar disk properties, in particular on its size and temperature. Unfortunately, presently both are poorly known and this prevents detailed quantitative studies of these effects. Finally, we note that the pulsar wind – disk interaction should have significant impact disk matter leading to a significant heating.

To illustrate the possible impact of these effects, we performed model calculations for three specific cases: (a) assuming high stellar wind ram pressure with a corresponding value of $\eta = 1.1 \times 10^{-3}$, and hot disk region with temperature $T_{\rm disk} = 10^4$ K; (b) assuming $\eta = 1.1 \times 10^{-3}$ and a lower temperature of the disk $T_{\rm disk} = 2.8 \times 10^3$ K; and (c) assuming $\eta = 0.05$ and $T_{\rm disk} = 2.8 \times 10^3$ K. The corresponding calculations are presented in Fig. 2, where we show SED of IC radiation from the unshocked pulsar wind for the epoch of 35 days after the periastron passage, together with the gamma ray flux reported by *Fermi*/LAT for this epoch (Abdo et al. 2011). Note that the detection of gamma rays has been characterized as a flare, given the sudden dramatic increase (by an order of magnitude) of the gamma ray flux. We relate this to the increase of the length of the unshocked wind after the pulsar exit from the disk, i.e. a fast transition between the cases (b) and (c) in Fig. 2. During the first 1-2 weeks of this epoch the pulsar is located close to the disk, and therefore the wind zone is intensively illuminated by the photons of the disk. Apparently the dominance of the infra red (IR) component of the disk over the optical radiation of the star, and the upper limit on the Lorentz factor of the wind $\Gamma_0 \leq 10^4$, derived from the *Fermi* observations during the periastron passage (see above), explain quite naturally the significantly softer spectrum of gamma rays observed during the flare (Abdo et al. 2011; Tam et al. 2011). From Fig. 2 one can see that with a reasonable set of model parameters, first of all, η, $T_{\rm disk}$, and Γ_0, one can explain both the spectral shape and the absolute flux of gamma rays during the flare. With a slightly different choice of parameters than the ones used in Fig. 2 we can provide, in principle, an almost perfect fit to the observational results. However, given the many uncertainties related the complex character of the interaction of the wind with the disk, such a "perfect fit" would not mean much. Instead we would like to emphasize two, in our view, more important consequences of this interpretation. First, it implies that the Lorentz factor of the wind cannot be significantly smaller than 10^4 given that the energy of the IC photons in the Thomson regime scales as $E_\gamma \propto T_{\rm d}\Gamma_0^2$. On the other hand, the analysis of Fermi observations during the periastron passage constrains the wind Lorentz factor to $\Gamma_0 \leq 10^4$. Thus if the interpretation of the flare is correct, the wind Lorentz factor should be quite close to 10^4. Secondly, the flux of gamma rays detected by *Fermi* is very close to the spin-down luminosity of the pulsar. Even assuming 100% efficiency of the IC radiation, i.e. conversion of the mechanical energy of the wind to gamma radiation, this would imply that more than 50% of the pulsar spin-down power is converted to the kinetic energy of the wind. This is a clear indication that somewhere between the pulsar magnetosphere and the termination point, the wind is accelerated, i.e. electromagnetic energy (Poynting flux) is converted to the kinetic energy of relativistic electrons.

3. Discussion

In this letter we propose a model to explain the recent *Fermi* observations of gamma rays from PSR B1259−63/LS 2883. We suggest that the detected signal is produced at the interaction of the cold pulsar wind with external photon fields. Importantly, to reach the flux level of the detected flare, an additional radiation component is required. Emission from the heated circumstellar disk can perfectly play this role. The Comptonization of the cold unshocked wind by the stellar disk emission proceeds in a quite specific way. Inside the disk it is suppressed because of the high pressure in the disk; the wind appears quite "short", and therefore does not have time to up-scatter sufficient number of optical and IR photons to produce detectable fluxes of gamma rays. On the other hand, outside the disk the density of the stellar optical photons generally dominates over the density of IR photons. But in the immediate vicinity of the disk, where the IR density is still very high, and, at the same time, the wind terminates quite far from the pulsar, the optical depth for Compton scattering can be as large as 1. Thus one may expect a very effective, close to 100% efficiency of transformation of the rotational energy of the pulsar to high energy gamma rays via Comptonization of the cold ultrarelativistic wind.

In the suggested scenario, the departure of the wind from the disk will lead to gradual decrease of the disk emitted photon density and correspondingly to the reduction of the gamma ray flux. Qualitative estimates show that the decay of the gamma ray flux on time-scales of days can be explained by the speed of the departure of the pulsar from the disk. If this scenario is correct, then we should expect a similar effect during the entrance of the pulsar into the disk, namely a gradual increase of the gamma ray flux accompanied with the softening of the spectrum, and sharp reduction of the gamma ray flux at the entrance of the pulsar into the disk. Most likely *Fermi* did not detect such a behavior of the gamma ray flux before the periastron, so formally this could be considered as an argument against the suggested scenario. However, the uncertainties related to the stellar disk do not allow us to make such a claim, especially given the strong dependence of the gamma ray flux on the orientation of termination shock. For example, at the first pulsar exit from the disk, the termination shock is expected to expand towards the direction opposite to the observer. Obviously, this should not lead to any significant enhancement of the wind signal in the direction of the observer (see Fig. 3).

Another important issue is related to the 15 days delay between the appearance of the pulsed radio emission and the epoch of the GeV flare. A possible explanation is related to the actual value of the η parameter, at which the termination shock changes its geometry from the "closed" to the "open" one. According to Bogovalov et al. (2008) this transition occurs at $\eta \approx 10^{-2}$, i.e. at the value of η parameter exceeding by an order of magnitude the value expected in the stellar disk. Thus, the transformation of the shock should occur rather far away from the disk center. On the other hand, the epochs of the pulsar eclipse are separated by an angle smaller than π. Thus, it is possible that the disk becomes transparent for the radio emission at densities which are still sufficient for the effective termination of pulsar wind within the disk. This issue will be discussed in details elsewhere.

We should note that the observational data presented in Fig. 1 show some discrepancy between the results reported by two different groups (one cannot exclude that the slightly different flux integration intervals result in the discrepancy). While the data points from Tam et al. (2011) basically exclude the possibility of a pulsar wind with Lorentz factor $\Gamma_0 \simeq 10^4$ and $\Gamma_0 \simeq 10^5$. Indeed, given the quite low upper limits obtained in the energy range of 0.1 – 1 GeV, the emission component reported by Tam et al. (2011) should have a rather narrow peak between 2 and 10 GeV, and a possible interpretation of this peak could be the emission of the cold pulsar wind with $\Gamma_0 \simeq 3 \times 10^4$. On the other hand, the data reported by the Fermi collaboration (Abdo et al. 2011) excludes $\Gamma_0 > 10^4$, being marginally consistent with $\Gamma_0 \approx 10^4$.

Since the flux detected with *Fermi*/LAT during the flare episode approaches the spin-down luminosity of the pulsar, the interpretation of this event by the post-shock flow would require significant Doppler boosting of radiation. Indeed although there are some uncertainties related to the distance to the system and the actual mass of the neutron star, which may relax this energy requirement by a factor up to ≈ 10, a relatively broad energy distribution is expected to be formed at the pulsar wind termination shock. Thus, a detection of a flux exceeding 10% of the spin-down luminosity of the pulsar in a narrow energy band between 100 MeV and 1 GeV would demand significant relativistic boosting. Relativistic outflows are indeed formed at interactions of the pulsar and stellar winds (Bogovalov et al. 2008), and in this case the broad band emission can be affected by Doppler boosting (Khangulyan et al. 2008; Dubus et al. 2010). However, in this specific case one can anticipate certain arguments against this possibility. Namely, the Doppler boosting should also affect the X- and TeV gamma ray fluxes, but no flares so far have been detected at these energies. Also, one should note that the flux level of the Doppler boosted radiation can easily exceed the limit set by the spin down luminosity of the parent pulsar, but such events have not been so far detected. Instead the reported gamma ray flux is very close to the spin-down flux of the pulsar. Within the model of gamma radiation of the unshocked wind, this coincidence can be naturally explained given the fact that the rotational energy of he pulsar is fully converted to the wind kinetic energy, and the inverse Compton scattering can convert, at the presence of adequate photon gas with Thompson optical depth exceeding 1, the wind kinetic energy to gamma rays with 100% efficiency. And finally, a strong argument in favor of the "relativistic cold wind" origin of the gamma ray flare is the lack of any remarkable activity during the flare at other wavelengths.

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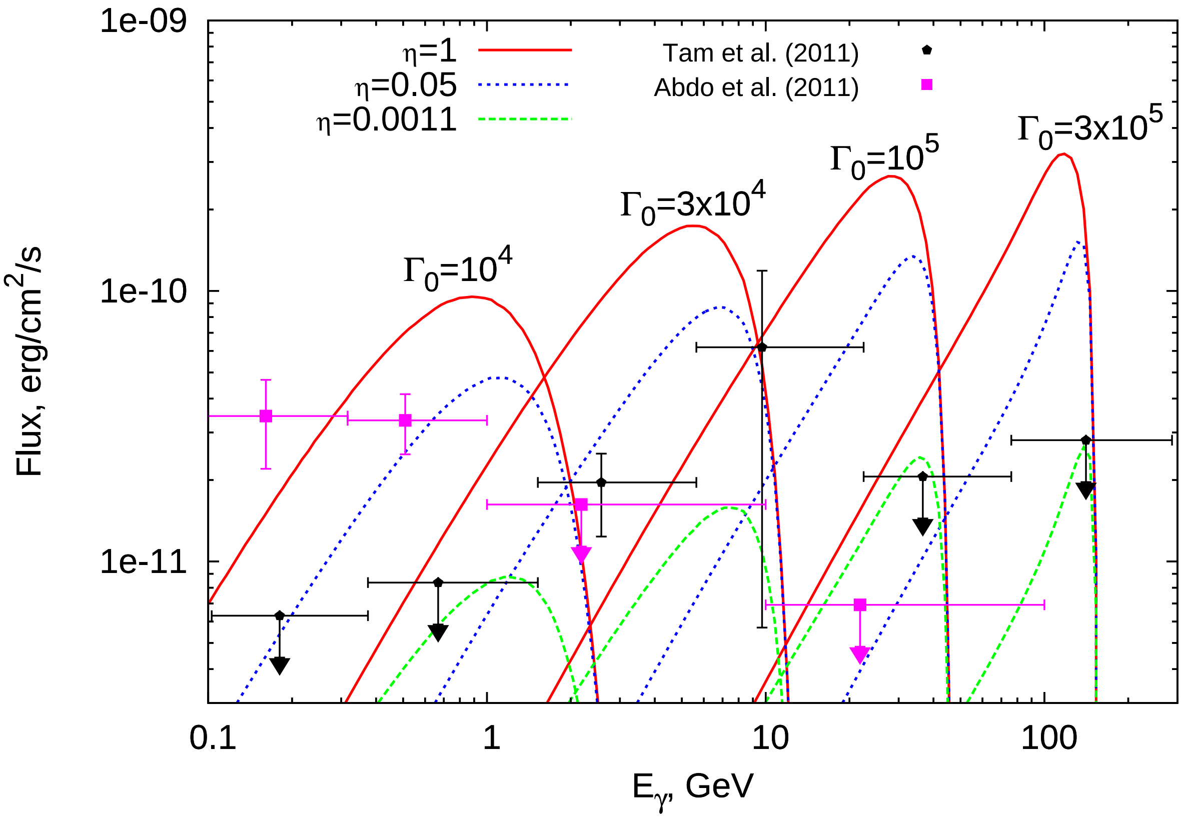

Fig. 1.— Spectral energy distributions of IC radiation from the unshocked pulsar wind averaged over a period from -35 to +18 days to periastron passage. The calculations were performed for different values of the η-parameter: $\eta = 1$ (solid lines), $\eta = 0.05$ (dotted lines) and $\eta = 1.1 \times 10^{-3}$ (dashed lines). The initial pulsar wind bulk Lorentz factor was assumed to be $\Gamma_0 = 10^4$, 3×10^4, 10^5 and 3×10^5. The calculations were performed for a spherical star with radius $R_* = 6.2 \times 10^{11}$cm and surface temperature $T_* = 3 \times 10^4$K (see for details Negueruela et al. 2011; Khangulyan et al. 2011). The observational points correspond to the pre-periastron flaring episode as were reported by Tam et al. (2011) (for the period from -35 to 0 days to periastron; shown with filled pentagons); and Abdo et al. (2011) (for the period from -28 to 18 days to periastron; shown with filled squares). We note that the model calculations for the intervals exact intervals used by Abdo et al. (2011) and Tam et al. (2011) give very close results.

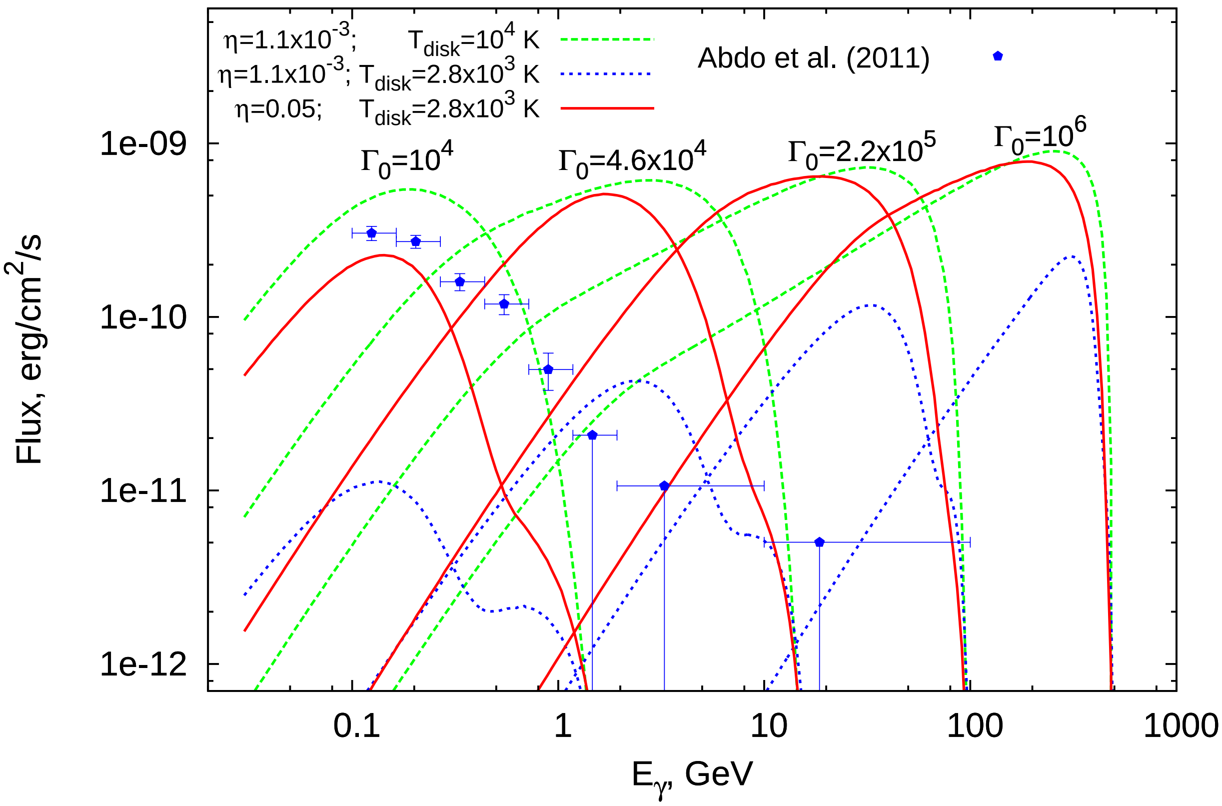

Fig. 2.— Possible impact of the disk emitted photons on the spectral energy distributions of IC radiation from the unshocked pulsar for the epoch 35 days after periastron passage. Two different situations are considered: interaction with a high ram pressure disk with $\eta = 1.1 \times 10^{-3}$ and temperature of 10^4 K (solid lines); a case of $\eta = 5 \times 10^{-5}$ and temperature of 2.8×10^3 K (dashed lines). The initial pulsar wind bulk Lorentz factor was assumed to be $\Gamma_0 = 10^4$,4.6×10^4, 2.2×10^5 and 10^6. The calculations were performed for the photon field with two contribution: radiation of spherical star with radius $R_* = 6.2 \times 10^{11}$cm and surface temperature $T_* = 3 \times 10^4$K; and the stellar disk emission with temperature, which was assumed to be Plankian with the disk temperature. The observational point correspond to the post-periastron flaring episode as was reported by Abdo et al. (2011) (for the period from 30 to 79 days to periastron; shown with filled pentagons).

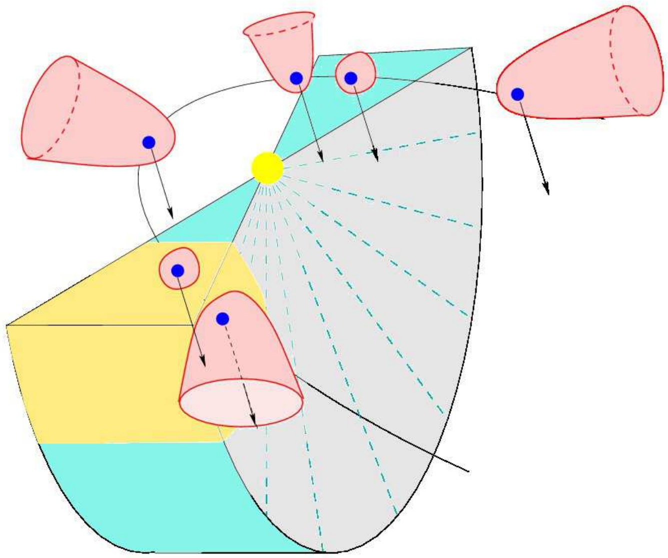

Fig. 3.— Sketch of the proposed scenario. The interaction of the pulsar wind with the stellar surrounding occurs in two different regimes: (i) collision with relatively diluted *polar wind*, when an "open", at the binary system scale, termination shock (shown by red lines for different epochs) is formed; (ii) interaction with dense stellar disk, when termination shock stands close to the pulsar. At the exit of the pulsar from the disk a fast transformation of the shock should occur. At the second exit of the pulsar from the disk, the pulsar wind zone (light red filled areas) is extended toward the observer (directions to the observer are shown by black arrows) dramatically enhancing the GeV gamma ray production rate. To achieve the detected flux level an additional photon field provided is needed. Such a radiation is provide by the heated disk (shown by yellow color).