Многокомпонентная структура гамма излучения двойной системы LS5039

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LS 5039 – one of the few known $\gamma$-ray loud binaries. HMXBs with the energy output dominated by emission in the GeV band.

Nature of the compact source is not known, but similarity with PSR B1259-63 suggests that it can be powered by a young pulsar.

Orbital period $P_{orb} \sim 3.9$ days.
Eccentricity $e = 0.35 \pm 0.04$
Optical companion O6.5V(f) $V=11.2$
Distance $d=2.5 \pm 0.1$ kpc

Compact object moves close to the surface of the massive star
Orbital separation at the periastron $\sim 2 R_*$, and $4 R_*$ at the apastron.

Similar orbital behaviour of the TeV and X-ray emission (Takahashi et al. 2009).

GeV has a maximum at the periastron and a suppression of the flux at the inferior conjunction (Abdo et al. 2009).
Previous models

- Explanation of both variability patterns, as well as of the energy dependence of the variability pattern provides a challenge for phenomenological models of the source. Several alternative explanations were proposed in the past.

- GeV emission can be produced in the same region as TeV and X-ray emission, but it is additionally modified by the interactions with the optical photons of the companion star (Takahashi et al. 2009).

- Alternatively GeV and TeV emission can be produced in two different region, either
  - the shocks at the head-on collision of the winds and the termination shock, caused by Coriolis forces on scales larger than the binary separation (Bosch-Ramon et al. 2011, 2012, Zabalza et al. 2013).
  - Petri & Dubus (2011) propose to locate region of GeV emission very close to the compact object, which they assume to be hidden pulsar. They assumed GeV to come from the IC scattering of the optical photons on the relativistic electrons of the striped pulsar wind before the shock.
5 years of Fermi/LAT observations

- 5 years of Fermi/LAT data results in twice better statistics in comparison with earlier works (Abdo et al. 2009; Hadasch 2012). The obtained phase averaged spectrum is consistent with one from Hadasch (2012). Longer exposure and advanced version of software allow us to better measure the flux in high energy tail above 10 GeV, and to measure the flux in 60-100 MeV energy range.
- Phase-averaged spectrum 0.1-10 GeV spectrum can be described as a cut-off powerlaw model with $\Gamma=2.11\pm 0.05$ and $E_{\text{cut}} = 3.0\pm 0.45$ GeV.
While at energies > 1 GeV the spectrum is almost unchanged with the orbital phase, low energy part demonstrates much more significant variability.
Below 100 MeV the light curve behaves similar to X-ray and TeV energy band, with the minimum at phase 0.2. At higher energies the minimum shifts to phases 0.5 (100 MeV–1 GeV) and 0.75 (1–3 GeV) in agreement with Abdo et al. (2009). The amplitude of variability is also energy dependent.
Broad band emission from the region close to the star consists of the synchrotron and IC components. The seed photons for the IC scattering are coming from the T~ 3x10^4 K star and have typical energy $\varepsilon$~10 eV. The strength of the magnetic field with the energy density in equipartition with the radiation energy density is

$$B_{eq} = (8\pi U_{rad})^{1/2} \approx 1.5 \times 10^2 \left[ \frac{T_\star}{3 \times 10^4 \text{ G}} \right]^2 \left[ \frac{d}{2R_\star} \right]^{-1} \text{ G}$$

$$\varepsilon_s \approx 5 \times 10^3 \left[ \frac{B}{100 \text{ G}} \right] \left[ \frac{E_e}{3 \times 10^{10} \text{ eV}} \right]^2 \text{ eV}$$

$$\varepsilon_{IC} \approx \varepsilon_s (E_e/m_e)^2 \approx 3 \times 10^{10} \left[ \frac{E_e}{3 \times 10^{10} \text{ eV}} \right]^2 \text{ eV}$$

Comparing gyroradius of high-energy electrons and synchrotron cooling distance:

$$E_{e,\text{max}} \approx 3 \times 10^{12} \left[ \frac{B}{100 \text{ G}} \right]^{-1/2} \text{ eV}$$

$$\varepsilon_{s,\text{max}} \approx 5 \times 10^7 \left[ \frac{B}{100 \text{ G}} \right] \left[ \frac{E_{e,\text{max}}}{3 \times 10^{12} \text{ eV}} \right]^2 \text{ eV} \approx 5 \times 10^7 \text{ eV}$$
Phase-averaged spectrum

- Within synchrotron interpretation of the modulated component the highest energy electrons efficiently loose energy before escaping from the source.

\[ D_s = 4 \times 10^{10} \left[ \frac{B}{100 \text{ G}} \right]^2 \left[ \frac{E_e}{3 \times 10^{10} \text{ eV}} \right]^{-1} \text{ cm} \]

- The injected power is roughly independent of the orbital phase and the only change in the pattern of the synchrotron emission could be the shift of the spectrum toward higher/lower energies, in response to the increase/decrease of the magnetic field.

- Maximum of the synchrotron emission in the energy band >100 MeV is observed around the periastron, where magnetic field is the strongest and the synchrotron spectrum shifts toward higher energies.

- This shift leads to the decrease of the X-ray flux close to periastron. Increasing magnetic field close to the periastron leads to stronger synchrotron loss and to the suppression of the IC emission in KN regime, which affects TeV energy range.
If high-energy particles leave the region in the interior of the binary orbit with \( v_{\text{esc}} \sim c \), then \( t_s \) and \( t_{\text{ic}} > t_{\text{esc}} \) at energies below 3GeV. In case of slow escape with the stellar wind synchrotron cooling time is larger than escape time only for electrons with energies below 30 MeV.

Electrons with low energies could spread around the system and produce extended synchrotron and IC emission on much larger distance scales, as observed in the radio band on the distance scales of 100 R*.

Case of slow escape could be immediately ruled out, because in this case the 30 MeV electrons could produce radio synchrotron emission in the nebula only if \( B_{\text{nebula}} > 100 \) G.
The IC emission of the larger scale nebula filled with electrons with energies $E < 3$ GeV reaches the energy $\sim 300$ MeV and should be visible to Fermi.

This extended nebular IC emission is only weakly modulated on the orbital time scale, because of the very large size of extended emission region, where the radiation and magnetic field are weaker and the cooling times of electrons become increasingly longer.
The extended nebula also loses high-energy electrons because of the escape to still larger distances.

In case of fast escape, even the highest energy, 3 GeV electrons would not be able to cool efficiently in the nebula and produce any significant synchrotron and IC flux.

Even for slow escape electrons with energies below 300 MeV could not be efficiently cooled in the nebula and escape toward still larger distances. This leads to the suppression of synchrotron power at the energies below GHz, as observed by GMRT (Bhattacharyya et al. 2012).
Conclusions

- Search for the orbital modulation of LS 5039 in Fermi/LAT data reveals different dependences of the flux on orbital phase for different energy bands.
- At low (<100 MeV) energies flux demonstrates strong variability with the minimum at orbital phase 0.3, close to one observed in X-rays and TeVs.
- With increase of the energy, the minimum shifts toward the orbital phase 0.5–0.7, observed previously in GeV range.
- Simultaneously with the increase of energy the significance of the variability decreases.
- The observed orbital folded lightcurves can be interpreted as a sum of steady (dominant at GeV energies) and significantly variable (dominant at lower energy) components.
- These components are readily explained in terms of proposed two-component model. In this model variable component is explained by synchrotron emission from the interior part of the binary, while the steady one is the IC counterpart of extended radio synchrotron emission from a much larger than the binary system size region.
Спасибо за внимание!