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High-Energy Neutrino Emission from Binary X-Ray Sources.

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Summary. — Recently γ -rays up to 10^{16} eV were observed from Cyg X3, Vela X1 and LMC X4. This is a strong indication that protons (or nuclei) are accelerated in the vicinity of the accreting pulsar. We discuss in this paper the production of high-energy neutrinos associated with the γ -ray production. We show that on the basis of observational parameters of the three binary systems, the time average of the ratio of the neutrino luminosity to the γ -ray luminosity will be $L_\nu/L_\gamma \sim 30$. The neutrino flux will be modulated with the orbital period of the system and the neutrino light curve will be determined by the density profile of the companion star. In general some of the X-ray binaries can be both UHE γ -ray and neutrino emitters with a neutrino luminosity comparable to their X-ray luminosity. The brightest of these could be detected by future neutrino telescopes such as DUMAND and MACRO at Gran Sasso.

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Binary X-ray stars were discovered about ten years ago by GIACCONI and collaborators (^{1,2}). Since then ~ 60 systems of this type were observed and they represent $\sim 80\%$ of the known galactic X-ray sources with $L_x \geq 10^{33}$ erg s⁻¹. In many of these systems have been found X-ray pulsars with periods ranging from 69 ms to 835 s. The coherence of the pulsations, and the secular decrease in their period, establishes beyond doubt that each of these systems contains a magnetized neutron star accreting material and angular momentum from a nondegenerate companion (^{3,4}). Measurements of the orbital elements of some systems require that the mass of the pulsar be consistent with that expected for a neutron star. Light curves from many of the pulsars indicate that the emission must be beamed (⁵). Such beaming and cyclotron features in the X-ray spectra suggest a large magnetic field $\sim 10^{12}$ G at the surface of the pulsar.

Recently three of this systems were discovered to be strong emitters of particles which produce extensive air showers in the atmosphere (⁶⁻⁹). The identification of these new sources with the binary systems is strongly suggested by the periodicity of the UHE emission which is fairly coincident with the binary period of the X-ray sources. Therefore we are forced to admit that the air showers are caused by low-mass neutral particles which can travel through the galactic magnetic field from distances of tens of kpc, conserving both directionality and time coherence. The most natural assumption is that the air showers are produced by ultrahigh-energy (UHE) γ -rays.

This detection was very surprising because the binary X-ray sources show a thermal X-ray spectrum with no associated γ -ray emission in the COS-B energy range (¹⁰). The only possible exception could be Cyg X3, which was detected in the SAS-2 survey (¹¹), but not by COS-B. If the showering particles are photons, the most plausible interpretation of the production of these photons require acceleration of protons or nuclei up to energy of the order of $\sim (10^4 \div$

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(⁶) M. SAMORSKY and W. STAMM: *Astrophys. J. Lett.*, **268**, L17 (1983).

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(⁸) R. J. PROTHEROE, R. W. CLAY and P. R. GERHARDY: *Astrophys. J. Lett.*, **280**, L47 (1984).

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(¹⁰) G. F. BIGNAMI and W. HERMES: *Annu. Rev. Astron. Astrophys.*, **21**, 67 (1983).

(¹¹) R. C. LAMB, C. E. FICHEL, R. C. HARTMAN, D. A. KNIFFEN and D. J. THOMSON: *Astrophys. J. Lett.*, **212**, L63 (1977).

$\div 10^5$) TeV. WDOWCZYK and WOLFENDALE⁽¹²⁾ have pointed out that ~ 30 sources of this strength can feed the Galaxy its entire content in cosmic-ray particles. But even more puzzling was the detection of a modulated flux of muons with energy $E_\mu \geq (0.5 \div 1)$ TeV from the direction of Cyg X3 claimed by the SOUDAN group⁽¹³⁾ and confirmed by D'ETTORRE-PIAZZOLI at this conference⁽¹⁴⁾. This new result cannot be interpreted in the framework of the known particle physics⁽¹⁵⁾.

VESTRAND and EICHLER⁽¹⁶⁾ have proposed the simple model, schematically shown in fig. 1, which can explain the production of UHE γ -rays in binary system. In this model protons (or nuclei) accelerated in the vicinity of the pulsar are driven by the magnetic field to hit the surface of the companion. In fact HILLAS⁽¹⁷⁾ has shown that the production of UHE γ -rays must occur far from the pulsar, otherwise the γ -rays would be self-absorbed by pair creation in its strong magnetic field of the pulsar.

Acceleration of protons in the polar cups of the pulsar was originally advocated by EICHLER and VESTRAND⁽¹⁸⁾. But this mechanism is inconsistent with the slow spin rates of the pulsars in Vela X1 and LMC X4 systems. A more appealing mechanism was proposed by CHANMUGAM and BRECHER⁽¹⁹⁾.

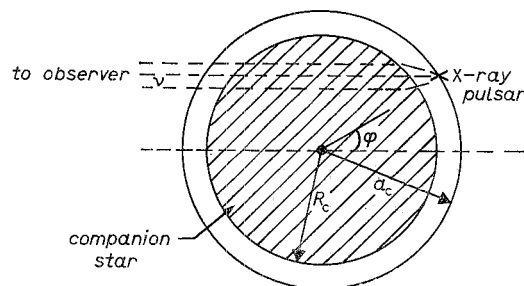


Fig. 1. - Model for UHE γ -ray and neutrino production in X-ray binary systems (after VESTRAND and EICHLER⁽¹⁶⁾).

⁽¹²⁾ J. WDOWCZYK and A. W. WOLFENDALE: *Nature (London)*, **305**, 609 (1983).

⁽¹³⁾ M. L. MARSHAK, J. BARTELT, H. COURANT, K. HELLER, T. JOYCE, E. A. PETERSON, K. RUDDICK, M. SHUPE, D. S. AYRES, J. DAWSON, T. FIELDS, E. N. MAY, L. E. PRICE and K. SIVAPRASAD: *Phys. Rev. Lett.*, **54**, 2079 (1985).

⁽¹⁴⁾ G. BATTISTONI, E. BELLOTTI, C. BLOISE, G. BOLOGNA, P. CAMPANA, C. CASTAGNOLI, A. CASTELLINA, V. CHIARELLA, A. CIOCIO, D. CUNDY, B. D'ETTORRE-PIAZZOLI, E. FIORINI, P. GALEOTTI, E. IAROCCI, C. LIGUORI, G. MANNOCCHI, G. MURTAS, P. NEGRI, G. NICOLETTI, P. PICCHI, M. PRICE, A. PULLIA, S. RAGAZZI, M. ROLLIER, O. SAAVEDRA, L. SATTI, P. SERRI, S. VERNETTO and L. ZANOTTI: *Phys. Lett. B*, to be published.

⁽¹⁵⁾ M. V. BARNHILL III, T. K. GAISSER, T. STANEV and F. HALZEN: preprint MAD-PH-243 (April 1985).

⁽¹⁶⁾ W. T. VESTRAND and D. EICHLER: *Astrophys. J.*, **261**, 251 (1982).

⁽¹⁷⁾ A. M. HILLAS: *Nature (London)*, **312**, 50 (1984).

⁽¹⁸⁾ D. EICHLER and W. T. VESTRAND: *Nature (London)*, **307**, 613 (1984).

⁽¹⁹⁾ G. CHANMUGAM and K. BRECHER: *Nature (London)*, **313**, 767 (1985).

They suggest that the large electrostatic potential required for the particle acceleration is induced by dynamo effect of the pulsar magnetic field, in the highly ionized plasma forming the X-ray emitting accretion disk around the pulsar itself. In this case the particle luminosity of the object is related to the accretion rate and to the mass M_x of the collapsed object, being $L_x \ll L_p \ll L_E$, where $L_E \simeq 1.38 \cdot 10^{38} (M_x/M_\odot)$ erg/s is the Eddington luminosity, and L_x is the X-ray luminosity. It is worth to notice that the UHE γ -ray luminosity is, in fact, proportional to the X-ray luminosity in the three sources detected up to now, as predicted by the acceleration model.

Neutrino production by hadronic cascade in cosmic sources was computed by BERETZINSKY and VOLINSKY⁽²⁰⁾, STENGER⁽²¹⁾ and more recently by LEE and BLUDMAN⁽²²⁾ and GAISSER and STANEV⁽²³⁾. All these computations are based on extremely idealized models of the matter distribution in the source. Therefore, their results cannot be applied to predict the emissivity of complex systems such as the X-ray binaries.

First of all the matter distribution in the model depicted in fig. 1 is extremely anisotropic. Therefore, whereas the γ -rays are emitted only when the beam of particles hits the limb of the star, the neutrino are emitted mainly during the occultation of the pulsar. Hence the duration of the γ -ray flashes will be approximately

$$(1) \quad \tau_\gamma \simeq P \times \frac{H_c}{R_c},$$

where P is the orbital period, H_c the scale height of the star's atmosphere and R_c its radius. Neutrino emission per orbit will last

$$(2) \quad \tau_\nu \simeq \frac{P R_c}{\pi a_c},$$

where a_c is the separation of the system. We can expect, therefore, that

$$(3) \quad L_\gamma \ll L_\nu \ll L_\gamma \frac{\tau_\nu}{\tau_\gamma}$$

assuming $\varepsilon_\gamma \simeq \varepsilon_\nu \simeq \varepsilon_\gamma$ as obtained from ref. (21).

Another important point is that the density of the external layers of the companion star in the system is far from being uniform. In fact a high-energy

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⁽²¹⁾ V. J. STENGER: *Astrophys. J.*, **284**, 810 (1984).

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proton penetrates deep inside the photosphere of the star. Hence the hadronic cascade develops in a medium with nearly exponential density distribution. This situation is similar to the development of showers in the Earth's atmosphere.

Analytical solutions of the cascade equation in an exponential atmosphere are reported by DAR⁽²⁴⁾ for an input spectrum of protons

$$(4) \quad F_p = K_p \times E_p^{-\gamma}$$

in the form

$$(5) \quad F_\nu = K_\nu \frac{E_\nu^{-\gamma}}{(1 + E_\nu/E_k)},$$

where E_k is the critical energy for pion re-interaction before decay:

$$(6) \quad E_k = \frac{m_\pi c H_c}{\tau_\pi},$$

where m_π and τ_π are the mass and lifetime of the charged pions, c the light velocity and H_c is the scale height of the stellar photosphere.

The scale height parameter which enters in eq. (6) regulates the neutrino emission at high energies. Therefore at high energies the spectral index of the neutrino spectrum approaches $\gamma + 1$. The extension of the stellar atmosphere is determined by the effective temperature of the star and its surface gravity. Both these quantities according to the stellar evolution theory⁽²⁵⁾ are function of the mass of the star. Hence we can predict that the neutrino spectrum to be expected from binary system will depend on the mass of the companion star. BRADT and MCCLINTOCK⁽²⁶⁾ divide the binary X-ray systems into two classes: i) the massive systems, which have a large-mass early-type companion; ii) the low-mass systems including a late-type companion. This classification is extremely relevant also from the point of view of the neutrino spectrum. According to the above-referred considerations we expect that massive systems, like Vela X1 and LMC X4, will have a harder neutrino spectrum than a low-mass system like Cyg X3⁽²⁷⁾.

In their recent paper GAISSER and STANEV⁽²³⁾ have pointed out also that high-energy neutrinos are adsorbed in the body of star, during the occultation. This effect introduces a time-modulated high-energy cut-off in the neutrino

⁽²⁴⁾ A. DAR: *Phys. Rev. Lett.*, **51**, 227 (1983).

⁽²⁵⁾ D. D. CLAYTON: *Principles of Stellar Evolution and Nucleosynthesis* (McGraw-Hill, New York, N. Y., 1968).

⁽²⁶⁾ H. V. D. BRADT and J. E. MCCLINTOCK: *Annu. Rev. Astron. Astrophys.*, **21**, 13 (1983).

⁽²⁷⁾ Very similar results are obtained by F. W. STECKER, A. K. HARDING and J. J. BARNARD: preprint GSFC (1985).

spectrum. Very roughly the cut-off energy in the time-averaged neutrino spectrum will be

$$(7) \quad E_c \simeq 10 \frac{R_c^3}{M_c},$$

where R_c and M_c are respectively the radius and the mass of the companion star in solar units.

In conclusion we find that the neutrino spectrum emitted by a binary system is similar to the one sketched in fig. 2. In this spectrum are present a break due to the pion reinteractions and a cut-off due to the self-absorption of neutrinos in the stellar interiors. The position of this two spectral features depends on the mass of the companion star. In general we will expect that the neutrino spectrum of a low-mass system will be softer than the one of a massive system.

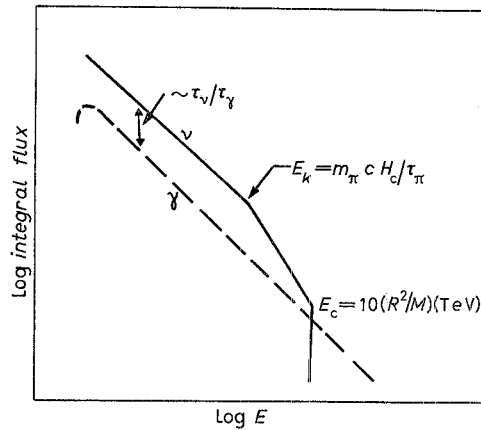


Fig. 2. — Spectral distribution of neutrinos from binaries. The dashed line is the associated γ -ray emission from π^0 decay.

In table I we have reported the relevant physical parameters for the three UHE binaries so far detected. We have indicated also the break and cut-off energy estimated from eqs. (6) and (7). From the point of view of the total neutrino luminosity the effect of density is not relevant, but from the point of view of the detectability, the effect of softening due to the density of the companion star could be catastrophic. In fact STENGER⁽²⁸⁾ and GAISSER and STANEV⁽²⁹⁾ have shown that undersea or underground detectors are sensitive only to the extreme end of the neutrino spectrum, well above 10 TeV.

⁽²⁸⁾ V. J. STENGER: preprint HDC-4-85 (April 1985).

⁽²⁹⁾ T. K. GAISSER and T. STANEV: *Phys. Rev. D*, **31**, 2770 (1985).

TABLE I. - *Physical parameter of UHE binaries.*

	Cyg X3	Vela X1	LMC X4
Distance	12 kpc	1.4 kpc	55 kpc
$L_x(2 \simeq 10 \text{ keV})$	$\sim 10^{38} \text{ erg/s}$	$6 \times 10^{36} \text{ erg/s}$	$4 \times 10^{38} \text{ erg/s}$
Period	4.8 h	8.97 d	1.4 d
spectral type	?	<i>B05 Ib</i>	<i>O7 III - V</i>
M_c	$4 - 10 M_\odot$	$20 M_\odot$	$17 M_\odot$
R_c	$2 R_\odot$	$30 R_\odot$	$8.9 R_\odot$
a_c/R_c	1.05	1.46	1.3
H_c	$\sim 10^7 \text{ cm}$	$2 \times 10^8 \text{ cm}$	$3 \times 10^8 \text{ cm}$
E_b	1.8 TeV	35 TeV	50 TeV
E_c	5.6 TeV	450 TeV	$\sim 50 \text{ TeV}$
τ_ν/τ_γ (*)	~ 30	~ 27	~ 30

(*) The τ_ν/τ_γ value is deduced from measured γ pulse shape and has to be considered an upper limit.

Generally speaking, if the same acceleration mechanism is at work in any X-ray emitting binary system, we can expect a strong UHE γ -rays and neutrino emission from extremely close system, with ratio R_c/a_c close to unity. Among these systems the massive ones which include an early-type companion star have a harder neutrino spectrum, being the cut-off energy proportional to the ratio R_c^2/M_c .

* * *

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● RIASSUNTO

Recentemente è stata rivelata emissione di raggi gamma con energia sino a 10^{16} eV da Cyg X3, Vela X1 ed LMC X4. Questa osservazione indica che protoni (o nuclei) sono accelerati nella vicinanza della pulsar contenuta in questi tre sistemi binari. In questo lavoro si calcola la produzione di neutrini di alta energia, associata alla produzione di raggi gamma. Il risultato ottenuto è che, tenendo conto dei parametri dedotti dalle osservazioni spettroscopiche dei tre sistemi considerati, il rapporto tra la luminosità in neutrini e la luminosità gamma è $L_\nu/L_\gamma \sim 30$. Inoltre il flusso di neutrini sarà modulato con il periodo binario del sistema e la curva di luce dei neutrini sarà determinata dalla distribuzione di densità della stella compagna. In generale alcune delle binarie X possono essere sorgenti sia di gamma di altissima energia che di neutrini, con una luminosità in neutrini paragonabile alla luminosità in raggi X. Le più intense tra queste potranno essere osservate da futuri telescopi per neutrini come DUMAND o MACRO.

Испускание высокоэнергетичных нейтрино из бинарных рентгеновских источников.

Резюме (*). — Недавно γ -кванты с энергиями вплоть до 10^{16} эВ наблюдались из Cyg X3, Vela X1 и LMC X4. Это является указанием, что протоны (или ядра) ускоряются в окрестности аккретирующего пульсара. Мы обсуждаем в этой статье образование высокоэнергетичных нейтрино, которое связано с рождением γ -квантов. Мы показываем, что на основе наблюдаемых параметров для трех бинарных систем среднее по времени отношение интенсивности испускания нейтрино к интенсивности испускания γ -квантов составляет $L_\nu/L_\gamma \sim 30$. Модуляция потока нейтрино определяется орбитальным периодом системы, а кривая яркости нейтрино определяется профилем плотности сопутствующей звезды. Обычно рентгеновские бинарные системы могут представлять источники γ -квантов сверхвысоких энергий и источники нейтрино, причем интенсивность испускания нейтрино сопоставима с интенсивностью рентгеновского излучения. Наиболее яркие из них могут быть зарегистрированы в будущем с помощью нейтринных телескопов, таких как DUMAND и MACRO в Гран Сассо.

(*) *Переведено редакцией.*

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