TeV Neutrinos from Galactic Microquasar Jets

D. Guetta\textsuperscript{1}, C. Distefano\textsuperscript{2}, A. Levinson\textsuperscript{3} & E. Waxman\textsuperscript{4}
\textsuperscript{1} Osservatorio di Arcetri, L.E. Fermi 2, Firenze
\textsuperscript{2} Laboratori nazionali del Sud, INFN, Catania
\textsuperscript{3} School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
\textsuperscript{4} Department of Condensed Matter Physics, Weizmann Institute, Rehovot 76100, Israel.

Abstract. We discuss the possibility that microquasar jets may be powerful emitters of TeV neutrinos. We estimate the neutrino fluxes produced by photopion production in the jets of a sample of identified microquasars and microquasar candidates, for which available data enables rough determination of the jet parameters. We demonstrate that in several of the sources considered, the neutrino flux at Earth, produced in events similar to those observed, can exceed the detection threshold of a km\textsuperscript{2} neutrino detector. Sources with bulk Lorentz factors larger than those characteristic of the sample considered here, directed along our line of sight may be very difficult to resolve at radio wavelengths and hence may be difficult to identify as microquasar candidates. However these sources can be identified through their neutrino and gamma-ray emission.

1. Introduction

The composition of microquasars jets is yet an open issue. The synchrotron emission both in the radio and in the IR is consistent with near equipartition between electrons and magnetic field, which is also implied by minimum energy considerations \cite{1}. However, the dominant energy carrier in the jet is presently unknown (with the exception of the jet in SS433). A possible diagnostic of hadronic jets is emission of TeV neutrinos \cite{3}. As shown in reference \cite{3}, for typical microquasar jet parameters, protons may be accelerated in the jet to energies in excess of $\sim 10^{16}$ eV. The interaction of these protons with synchrotron photons emitted by thermal electrons is expected to lead to 1–100 TeV neutrino emission. The predicted fluxes are detectable by large, km\textsuperscript{2}-scale effective area, high-energy neutrino telescopes, such as the operating south pole detector AMANDA \cite{4} and its planned 1 km\textsuperscript{2} extension IceCube \cite{5}, or the Mediterranean sea detectors under construction (ANTARES \cite{6}; NESTOR \cite{7}) and planning (NEMO \cite{8} and \cite{9} for a recent review).

In this paper we consider a class of identified Galactic microquasars with either persistent jets or documented outbursts. For each source we provide, for illustrative purposes, our model prediction for the neutrino flux that should have been emitted during particular events, using radio data available in the literature. Although the temporal behavior of many of these sources may be unpredictable, we demonstrate that some of the sources could have been detected by a neutrino telescope with effective area larger than km\textsuperscript{2} (in some cases even 0.1 km\textsuperscript{2}) had such a detector been in operation during the time of the recorded events and, therefore, propose that they should be potential targets for the planned neutrino
telescopes. In addition we consider a list of XRBs thus far unresolved at radio wavelengths, that are believed to be microquasar candidates. In §2 we briefly discuss the neutrino production mechanism in microquasars. In §3 we use observational data available for each source to estimate the jet parameters, and then use these parameters to derive the expected neutrino flux. The number of neutrino induced muon events in km$^2$-scale neutrino telescopes is derived in §4. The implications of our results are briefly discussed in §5.

2. Internal shock model for microquasars

In this section we give a brief outline of the model proposed by Levinson & Waxman (2001) for production of neutrinos in microquasars with the purpose to introduce the parameters relevant for the present analysis. The model assumes that on sufficiently small scales ($\lesssim 10^{11}$ cm), unsteadiness of the jet leads to the formation of internal shocks that can accelerate protons and electrons to a power law distribution. For typical jet parameters, the maximum proton energy is roughly $10^{16}$ eV in the jet frame. Protons can interact with both the external X-ray photons emitted by the accretion disc, and the synchrotron photons produced inside the jet by the shock heated electrons, leading to pion production and consequent neutrino emission. In order for photomeson production to take place, the comoving proton energy must exceed the threshold energy for $\Delta$-resonance, $\approx 10^{14}$ eV for interaction with the external photons and $\approx 10^{13}$ eV for interaction with synchrotron photons.

Charged pions produced in photo-meson interactions decay to produce neutrinos, $\pi^+ \rightarrow \mu^+ + \nu_{\mu} \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$. In a single collision, a pion is created with an average energy that is $\approx 20\%$ of the proton energy. This energy is roughly evenly distributed between the final $\pi^+$ decay products, yielding a neutrino energy that is $\approx 5\%$ of the proton energy. The neutrino signal is dominated by neutrinos in the energy range of 1 to 100 TeV. The fraction of proton energy converted into pions, $f_\pi$, depends on the jet Lorentz factor, $\Gamma$, and on the kinetic luminosity of the jet, $L_{jet}$ (see [2] for details).

The expected neutrino flux (energy per unit area per unit time) of $\gtrsim 1$ TeV muon neutrinos at Earth from a jet ejection event is

$$f_{\nu_\mu} \simeq \frac{1}{2} \eta_p \frac{f_\pi \delta^4 L_{jet}}{8 \pi D^2}.$$  (1)

where $\delta = \left[ \Gamma(1 - \beta \cos \theta) \right]^{-1}$ is the Doppler factor of the jet ($\theta$ is the angle between the jet axis and our line of sight), $\eta_p \sim 0.1$ is the fraction of $L_{jet}$ carried by accelerated protons, and $D$ is the source distance.

3. Jet parameters and neutrino fluxes

In order to determine the neutrino flux from the main quantity to be estimated is the kinetic power of the jet. We have used two different methods for the sources with the relativistic jets resolved in the radio band (resolved microquasars) and for the XRBs observed as point like sources, such as GX 339-4, henceforth referred to as unresolved microquasars [10].
3.1. Resolved microquasars

In events that have been monitored with sufficiently good resolution, it is often possible to obtain a rough estimate of the characteristic source parameters, in particular the bulk speed of the jet, the angle between the jet axis and the sight line, and the size of the emitting blob. $L_{jet}$ is estimated in the following way:

for a flux density $S_\nu \propto \nu^{-1/2}$ of the radio source, implying an electron energy distribution $dn_e/d\epsilon_e \propto \epsilon^{-2}$, we estimate the minimum energy carried by electrons and magnetic field, obtained for a magnetic field [e.g. [1]]:

$$B_* = 3.6 \left[ \ln(\gamma_{\text{max}}/\gamma_{\text{min}}) \frac{T_{B6}}{l_{15}} \right]^{2/7} \frac{\nu_9^{5/7}}{\delta} \text{mG},$$

(2)

where $\nu = \nu_9 \cdot 10^9$ Hz, $l = l_{15} \cdot 10^{15}$ cm is the size of the emission region, $\gamma_{\text{max}}$ and $\gamma_{\text{min}}$ are the maximum and minimum electron random Lorentz factors as measured in the jet frame, and $T_B = 10^6 T_{B6}$ K is the brightness temperature. The jet power then satisfy,

$$L_{jet} \geq 0.3 c (\Gamma l B_*)^2.$$

(3)

For the numerical estimates that follow we conservatively assume $\gamma_{\text{max}}/\gamma_{\text{min}} = 100$. In Table 1 we report our estimates of the jet power and of the neutrino flux expected at Earth, calculated using equations 1 and 3 and adopting the source parameters quoted in literature. The two values of the periodic source LS I +61°303 (P~26.5 days) refer respectively to bursting and quiescent states observed by Massi et al. (2001) [11]. The distance of V4641 Sgr, and therefore the jet parameters, is uncertain. We report calculations for both the values of $D$ present in literature [12] and [13]. Several authors pointed out that the kinetic energy output of the SS433 jets can influence the radio emission of W50, moreover SS433 is the only microquasar that shows a strong H$\alpha$-line emission from the jets [14, 15, 16]. In our estimate we assume the conservative value of $L_{jet} \sim 10^{39}$ erg/sec suggested by Margon (1984)[17].

3.2. Unresolved microquasars

For the sources whose jet has not been resolved, we cannot deduce the value of $L_{jet}$ from Eq.(3), since $\Gamma$, $\delta$ and the size of the jet are not known. We follow instead a different line of argument. We estimate the jet synchrotron luminosity, assuming a spectral index $\alpha_R \sim 0.5$ for the emitted radiation [10]:

$$L_{\text{syn}} = 4\pi D^2 \frac{1}{1 - \alpha_R} S_{\nu_{\text{high}}} \nu_{\text{high}},$$

(4)

where $\nu_{\text{high}}$ is the highest observed frequency of synchrotron emission, and $S_{\nu_{\text{high}}}$ the flux density emitted at this frequency. Assuming that the total jet synchrotron luminosity is a fraction $\eta_R$ of the jet kinetic energy, carried by relativistic electrons and magnetic field, we estimate the total $L_{\text{jet}}$ as:

$$L_{\text{jet}} = \eta_e^{-1} \eta_r^{-1} L_{\text{syn}},$$

(5)

where $\eta_e$ denotes the fraction of bulk energy converted internal energy of electrons. For a typical value of $\alpha_R \sim 0.5$, that implies electrons do not cool fast on
scales that are resolved by the VLA. Assuming that emission at \( \nu_{\text{high}} \) originates from the same radius as the radio emission, for the typical parameters inferred for the resolved microquasars (B of tens of mG corresponding synchrotron frequency of about 10 GHz), electrons radiating at \( \nu_{\text{high}} \sim 10^{14} \) cannot lose more than \( \eta_p \sim 0.1 \) of their energy. The energy neutrino flux expected at Earth is:

\[
f_{\nu_{\mu}} = \frac{1}{2} f_{\pi} \eta_p L_{\text{jet}} / 8 \frac{\eta_p}{4\pi D^2} = \frac{1}{16(1 - \alpha_R)} \frac{\eta_p}{\eta_e} f_{\pi} \eta_r^{-1} S_{\nu_{\text{high}}} \nu_{\text{high}}. \tag{6}
\]

We have neglected in eqs. (4–6) corrections associated with the relativistic expansion of the jets. However, since these corrections are the same for both the synchrotron and neutrino emission, the estimate of neutrino flux in eqs. (6) is independent of such corrections. In Table 1 we quote, for a sample of unresolved microquasar candidates, our estimates of \( L_{\text{jet}} \) and \( f_{\nu_{\mu}} \), calculated from Eq. (5) and Eq. (6).

Recent observations with the VLBA array have confirmed the nature of microquasars for the source Cygnus X-1, revealing an extended jet-like feature extending to \( \sim 15 \) mas from a core region, with an opening angle of \(< 2^\circ \) \cite{18}. The authors suggest for this source a bulk motion velocity of \( \beta \sim 0.75 \) and a viewing angle of \( \theta \sim 40^\circ \), corresponding to a Lorentz factor of \( \Gamma \sim 1.51 \) and a Doppler boost factor \( \delta \sim 1.55 \). Adopting these jet parameters and a quasi-steady emission of \( S_{\nu} \sim 5 \) mJy at \( \nu = 8.4 \) GHz, the kinetic luminosity, calculated from Eq. (3), is \( L_{\text{jet}} \sim 3.53 \cdot 10^{36} \) erg/sec. The new estimate of the \( L_{\text{jet}} \) for Cygnus X-1 is therefore consistent with the value in Tab. 1, obtained from the Eq. (5) for the unresolved sources.

4. Muon events expected in a km\(^2\)-scale detector

The detection of TeV neutrino fluxes from microquasars could be the first achievable goal for proposed underwater(ice) neutrino telescopes. In this section we calculate the rate of neutrino-induced muon events expected in a detector with an effective area of 1 km\(^2\). Since the signal is expected to be dominated by neutrinos of energy \( E_{\nu} \geq 1 \) TeV, for which the detection probability is \( P_{\nu_{\mu}} \sim 1.3 \cdot 10^{-6} E_{\nu,\text{TeV}} \) \cite{19}, we estimate the number of neutrino-induced muon events as:

\[
N_{\mu} \simeq 0.2 \eta_p \left[ f_{\pi} \delta^4 D_{22}^{-2} L_{\text{jet},38} A_{\text{km}^2} \Delta t_d \right]
\tag{7}
\]

where \( A_{\text{km}^2} \) is the effective detector area in km\(^2\) units, and \( \Delta t_d \) the duration of the observed burst measured in days. It is seen from eq. (3) that in microblazars (microquasars having their jets pointing in our direction), even single outbursts may be easily detectable by km\(^2\) detectors if the total energy release is of the order of that seen in GRS 1915 and GRO 1655 (\( L_{\text{jet}} \Delta t \sim 10^{43} \) ergs). In Table 1 we report the number of events expected in a detector with \( A_{\text{eff}} = 1 \) km\(^2\) during the bursts considered in section 3. In the case of persistent sources number of neutrino induced muon events is calculated for a 1 year period. In the same table, we also report the number of background atmospheric neutrino events collected in such a detector during the time \( \Delta t \), assuming a neutrino spectrum \( \phi_{\nu,\text{bkg}} \sim 10^{-7} E_{\nu,\text{TeV}}^{-2.5} \) cm\(^2\) sec sr for \( E_{\nu} > 1 \) TeV and for a detector angular resolution of 0.3\(^\circ\).
5. Discussion

There are large uncertainties involved in the derivation of the jet parameters for most of the sources listed in table 4. The best studied cases are perhaps GRS 1915+105, GRO J1655-40, and SS433. Nonetheless, we have demonstrated that if the jets in microquasars are protonic, and if a fraction of a few percent of the jet energy is dissipated on sufficiently small scales, then emission of TeV neutrinos with fluxes in excess of detection limit of the forthcoming, km$^2$ scale, neutrino telescopes is anticipated.

The present identification of microquasars, and the inferred distribution of their jet Lorentz factors, may be strongly influenced by selection effects. It is quite likely that the class of Galactic microquasars contains also sources with larger bulk Lorentz factors and smaller viewing angles, which should emit neutrinos with fluxes considerably larger than the extended microquasars discussed in this paper. Such sources may be identified via their gamma-ray emission with, e.g. AGILE and GLAST, or by their neutrino emission. The gamma-rays should originate from larger scales where the pair production opacity is sufficiently reduced. Predictions for AGILE and GLAST will be discussed in a forthcoming paper [20]. There are currently about 280 known XRBs [21, 22], of which $\sim$ 50 are radio loud. These may also be potential targets for the planned neutrino detectors. Our results quoted in Table 1 are consistent with experimental upper limits on neutrino fluxes from point sources set by MACRO [23], AMANDA [24] and SuperKamiokande [25].

References

1. Levinson, A. & Blandford, R. 1996, ApJ, 456, L29
2. Distefano, C., Guetta, D., Waxman, E. & Levinson, A. in press on ApJ. [astro-ph/0202200].
3. Levinson, A. & Waxman, E. 2001, Phys. Rev. Lett., 87,171101.
4. Andres, E., et al. 2000, Astropart. Phys. 13, 1.
5. IceCube Proposal, [http://pheno.physics.wisc.edu/icecube/proposal.html]
6. ANTARES Proposal 1997, astro-ph/9707136
7. Monteleoni, B. for the NESTOR collaboration, Proceedings of the XVII International Conference on Neutrino.
8. Riccobene G. for the NEMO collaboration, Proceedings of the ”Workshop on methodical aspects of underwater/ice neutrino telescopes”, Hamburg, 15-16 August 2001.
9. Halzen, F., 2001, in Intl Symp on High Energy Gamma Ray Astronomy, Heidelberg, June 2000.
10. Fender, R., 2001, Ap&SS Suppl., 276, 69.
11. Massi, M., et al. 2001, A&A, 376, 217.
12. Hjellming, R.M. et al. 2000, ApJ, 544, 977.
13. Orosz, J.A. et al. 2001, ApJ, 555, 498.
14. Begelman, M.C., et al. 1980, ApJ, 238, 722.
15. Davidson, K. & McCray, R. 1980, ApJ, 241, 1082.
16. Kirshner, R.P. & Chevalier, R.A. 1980, ApJ, 242, L77.
17. Margon, B. 1984, ARA&A, 22, 507.
18. Stirling, A.M. et al., 2001, 327, 1273.
19. Gaisser, T.K., Halzen F. & Stanev T. 1995, Phys. Rep., 258, 173.
20. Guetta, D., Distefano, C., Levinson, A. & Waxman, E. 2002, in preparation.
21. Liu Q.Z., van Paradijs J., & van den Heuvel E.P.J. 2000, A&AS, 147, 25.
22. Liu Q.Z., van Paradijs J., & van den Heuvel E.P.J. 2001, A&A, 368, 1021.
23. Ambrosio, M., et al. 2001, ApJ, 546, 1038.
24. Biron, A. 2002 PHD thesis, Univ. California, Berkley.
25. Okada A. 2001, in Proc. 36th Int. Conf. on High Energy Physics, ed. C. S. Lim & T. Yamanaka (Singapore: World Scientific).
26. Hjellming, R.M. & Mioduszewski, A. J., 1998, IAUC 6862.
27. Harmon, B.A. & Fishman, G.J. 1998, IAUC 6874.
28. Rupen, M.P. & Hjellming, R.M. 1998, IAUC 6938.
29. Mirabel, I.F. & Rodriguez, L.F 1999, ARA&A, 37, 409.
| Source name       | $L_{\text{jet}}$ (erg/sec) | $f_{\nu\mu}$ (erg/cm$^2$sec) | $\Delta t$ (days) | $N_{\nu\mu}$ | $N_{\nu\mu,bkg}$ (deg/0.3°)$^2$ |
|-------------------|-----------------------------|-------------------------------|-------------------|--------------|--------------------------------|
| **Resolved**      |                             |                               |                   |              |                                |
| CI Cam [26] [27]  | 5.66·10$^{36}$              | 2.23·10$^{-11}$               | 0.6               | 0.005        | 0.002                          |
| XTE J1748-288     | 1.84·10$^{38}$              | 3.07·10$^{-11}$               | 20                | 0.25         | 0.054                          |
| Cygnus X-3 [21]   | 1.71·10$^{38}$              | 4.02·10$^{-10}$               | 3                 | 0.48         | 0.008                          |
| LS 5039 [22]      | 8.73·10$^{35}$              | 1.69·10$^{-13}$               | persistent        | 0.02         | 0.986                          |
| GRO J1655-40 [23] | 1.60·10$^{39}$              | 7.37·10$^{-11}$               | 6                 | 0.18         | 0.016                          |
| GRS 1915+105 [34] | 2.45·10$^{39}$              | 2.10·10$^{-11}$               | 6                 | 0.05         | 0.016                          |
| Circinus X-1 [24] | 7.61·10$^{37}$              | 1.22·10$^{-11}$               | 4                 | 0.02         | 0.011                          |
| LS I 61°303       | 1.65·10$^{36}$              | 4.49·10$^{-12}$               | 7                 | 0.01         | 0.019                          |
| LS I 61°303       | 5.69·10$^{35}$              | 9.06·10$^{-13}$               | 20                | 0.01         | 0.054                          |
| XTE J1550-564     | 2.01·10$^{37}$              | 2.00·10$^{-12}$               | 5                 | 0.004        | 0.014                          |
| V4641 Sgr [42]    | 8.02·10$^{36}$              | 2.25·10$^{-11}$               | 0.3               | 0.003        | 0.001                          |
| V4641 Sgr [42]    | 1.17·10$^{39}$              | 3.25·10$^{-9}$                | 0.3               | 0.39         | 0.001                          |
| Scorpius X-1 [35] | 1.04·10$^{37}$              | 6.48·10$^{-13}$               | persistent        | 0.09         | 0.986                          |
| SS433 [17]        | 10$^{39}$                   | 1.72·10$^{-9}$                | persistent        | 252          | 0.986                          |
| **Unresolved**    |                             |                               |                   |              |                                |
| GS 1354-64 [46]   | 3.62·10$^{37}$              | 1.88·10$^{-11}$               | 2.8               | 0.02         | 0.008                          |
| GX 339-4 [41]     | 3.86·10$^{38}$              | 1.26·10$^{-9}$                | persistent        | 183.4        | 0.986                          |
| Cygnus X-1 [44]   | 1.45·10$^{36}$              | 1.88·10$^{-11}$               | persistent        | 2.8          | 0.986                          |
| GRO J0422+32 [43] | 4.35·10$^{37}$              | 2.51·10$^{-10}$               | 1÷20              | 0.1÷2        | 0.003÷0.1                      |
| XTE J1118+480     | 3.49·10$^{37}$              | 5.02·10$^{-10}$               | 30÷150            | 6÷30         | 0.081÷0.405                    |

30. Kotani, T. et al. 2000, ApJ, 543, L133.
31. Mioduszewski, A.J., et al. 2001, ApJ, 553, 766.
32. Paredes, J.M., et al. 2000, Science 288, 2340.
33. Hjellming, R.M.& Rupen M.P. 1995, Nature 375, 464.
34. Mirabel, I.F. & Rodriguez, L.F. 1994, Nature 371, 46.
35. Preston, R.A., et al. 1983, ApJ, 268, L23.
36. Hannikainen, D. et al. 2001, ApskSS, 276, 45.
37. Sánchez-Fernández C., 1999, A&A, 348, L9.
38. Fomalont, E.B., Geldzahler B.J. & Bradshaw C.F. 2001, ApJ, 553, L27.
39. Fomalont, E.B., Geldzahler B.J. & Bradshaw C.F. 2001, ApJ, 558, 283.
40. Fender, R.P. 2001, ApskSS Suppl., 276, 69.
41. Brocksopp, C. 2001, MNRAS, 323, 517.
42. Fender, R. 2001b, MNRA, 322, 31.
43. Corbel, S., et al. 2000, A&A, 359, 251.
44. Pooley, G.G., Fender, R.P. & Brocksopp C. 1999, MNRAS, 302, L1.
45. Shrader, C.R. 1994, ApJ, 434, 698.
46. Frontera, F. 2001, ApJ, 561, 1006.