pγ interactions in Galactic jets as a plausible origin of the positron excess

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ABSTRACT

The positron flux measured near Earth shows a rise with energy beyond 30 GeV. We show that this rise might be compatible with the production of positrons in pγ interactions in the jets of microquasars.

Key words: cosmic rays – Galaxy: centre.

1 INTRODUCTION

The electron and positron spectra measured by cosmic ray experiments (Boezio et al. 2000; DuVernois et al. 2001; Ackermann et al. 2012; Adriani et al. 2013; Aguilar et al. 2013) are interesting probes of nature. Electrons and positrons are injected into our Galaxy by cosmic ray sources and interactions during the propagation of cosmic ray protons and nuclei. The electron flux times the electron's energy cube (e.g. in units of GeV^2 m^{-2} s^{-1} sr^{-1}) is a useful representation of the spectrum. It is nearly constant in the energy range 10 GeV–1 TeV, and falls steeply at higher energies. The flux measured up to 4 TeV is composed of primary electrons and secondaries from various interactions. Production of pairs in cosmic ray interactions with matter and radiation, electrons emitting pairs in a magnetic field ($eB \rightarrow e^+e^-$) and $\gamma\gamma \rightarrow e^+e^-$ interactions contribute to the electron and positron fluxes equally. However, recent measurements of the positron flux show a rise beyond 30 GeV, which could have its origin either in conventional astrophysical sources or in dark matter annihilations (e.g. Finkbeiner et al. 2011; Gaggero et al. 2014; Cholis & Hooper 2014; Mauro et al. 2014; Mertsch & Sarkar 2014). A fraction of the positron flux measured up to 350 GeV originates from the pair-producing interactions mentioned above. Photohadronic interactions leading to the production of positrons ($p \gamma \rightarrow \Delta^+ \rightarrow \pi^+$ n, $\pi^+ \rightarrow e^+\nu_\mu \bar{\nu}_\mu \nu_e$) might also contribute to the observed positron spectrum (e.g. Gupta & Zhang 2008).

In this paper, we discuss the spectrum of positrons expected from these interactions in the jets of microquasars and how this excess flux can help to explain the recent measurements by the PAMELA (Adriani et al. 2013), Alpha Magnetic Spectrometer (AMS-02; Aguilar et al. 2013) and *Fermi* experiments (Ackermann et al. 2012). Microquasars have been considered earlier to explain the positron annihilation radiation at 511 keV (Guessoum, Jean & Prantzos 2006; Vila & Romero 2010). The possibility of explaining the observed positron excess at tens of GeV with microquasars has been mentioned in the review by Fan, Zang & Chang (2010). However, until now, there has been no computation available in the literature to demonstrate that this is indeed feasible, nor has there been any precise information about which process would make this excess happen. Here, we use the positron data to study this possibility quantitatively.

Our aim in this paper is not to provide a model of the inner microquasars (MQ) engine (or to construct a detailed SED of the photons emitted by it), which has been already been done in several papers, with different levels of detail. There are several situations where the pγ process dominates over leptonic and other hadronic interactions (pp) at high energies. For instance, see models A, C or D in Vila, Romero & Casco (2012). In these models, the target radiation field considered for the pγ interactions are the synchrotron photons of primary electrons, and there is a detailed description of the location of the acceleration region and the magnetic field dependence along the jet axis.

2 PHOTON NORMALIZATION

We denote the primary electron flux by $P_{e^-}(E_e)$, whereas the secondary electron flux produced in all pair-producing interactions, including processes both local to the astrophysical sources and during the propagation of cosmic rays in the Galaxy, is denoted by $F(E_e)$.

The injected fluxes of electrons and positrons are

$$Q_{e^-}(E_e) = P_{e^-}(E_e) + F(E_e),$$
$$Q_{e^+}(E_e) = \phi_{p\gamma \rightarrow \nu e^+}(E_e) + F(E_e). \tag{1}$$

Here, $\phi_{p\gamma \rightarrow \nu e^+}$ denotes the positron flux originating from the interaction channel ($p\gamma \rightarrow \Delta^+ \rightarrow \pi^+$n, $\pi^+ \rightarrow e^+\nu_\mu \bar{\nu}_\mu \nu_e$). The electrons and positrons lose energy inside the sources before their escape. The terms in equation (1) conceptually denote the injected flux after including the losses inside the sources.

We parametrize the photon spectrum in the jet frame (in units of GeV^{-1} cm^{-3}) of the pγ sources with a broken power law as

$$\frac{dn_\gamma(\epsilon_j)}{d\epsilon_j} = A \begin{cases} \epsilon_j^{-\gamma_1} & \epsilon_j < \epsilon_{br,j} \\ \epsilon_{br,j}^{\gamma_2-\gamma_1} \epsilon_j^{-\gamma_2} & \epsilon_j > \epsilon_{br,j} \end{cases}, \tag{2}$$

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where the spectral indices of the photon spectrum are γ_1 and γ_2. The break energy of the photon spectrum in the jet frame, $\epsilon_{\mathrm{br,j}}$, is related to its value in the observer frame as $\epsilon_{\mathrm{br}} = \delta_{\mathrm{D}}\epsilon_{\mathrm{br,j}}$. The Doppler factor δ_{D} is related to the Lorentz boost factor of the jet Γ_{j} and viewing angle in the observer's frame θ_{ob} as

$$\delta_{\mathrm{D}} = \Gamma_{\mathrm{j}}^{-1}(1 - \beta_{\mathrm{j}}\cos\theta_{\mathrm{ob}})^{-1}, \tag{3}$$

where β_{j} is the dimensionless speed of the jet frame with respect to the observer's frame on Earth. The normalization constant A can be calculated from the energy density in the jet as

$$U = \int_{\epsilon_{\gamma,\mathrm{min}}}^{\epsilon_{\gamma,\mathrm{max}}} \epsilon_{\mathrm{j}}\frac{\mathrm{d}n_{\gamma}(\epsilon_{\mathrm{j}})}{\mathrm{d}\epsilon_{\mathrm{j}}}\mathrm{d}\epsilon_{\mathrm{j}}, \tag{4}$$

where $\epsilon_{\mathrm{min,j}} \ll \epsilon_{\mathrm{br,j}} \ll \epsilon_{\mathrm{max,j}}$. This gives

$$A = \frac{U\epsilon_{\mathrm{br,j}}^{\gamma_1-2}}{\{[1/(\gamma_2 - 2)] - [1/(\gamma_1 - 2)]\}}, \tag{5}$$

with $\gamma_i \neq 2, i = 1, 2$.

3 Pγ INTERACTIONS AS A PLAUSIBLE SOURCE OF THE POSITRON EXCESS

There are several channels for pγ interactions, of which pγ → Δ^+ → π^+n and pγ → Δ^+ → π^0p are dominant, with nearly equal cross-sections (Muecke et al. 2000; Kelner & Aharonian 2008). For lower energies, pγ → pe$^+$e$^-$ becomes the dominant channel. The positively charged pions produced in pγ → Δ^+ → π^+n interactions decay to μ^+ and ν_μ. Subsequently, the μ^+ decay to e$^+$, $\bar{\nu}_\mu$ and ν_e. Three neutrinos and a positron are produced at the final state. Thus, pγ interactions lead to asymmetry in the number of electrons and positrons in the Galaxy. Each pγ interaction gives an extra positron.

The time-scale for the energy loss of a proton of energy $E_{\mathrm{p,j}}$ due to pion production, in the comoving frame, is (e.g. Waxman & Bahcall 1997)

$$t_\pi^{-1}(E_{\mathrm{p,j}}) = -\frac{1}{E_{\mathrm{p,j}}}\frac{\mathrm{d}E_{\mathrm{p,j}}}{\mathrm{d}t}$$
$$= \frac{c}{2\Gamma_{\mathrm{p,j}}^2}\int_{\epsilon_{\mathrm{th}}}^{\infty}\mathrm{d}\epsilon\,\sigma_\pi(\epsilon)\xi(\epsilon)\epsilon \times \int_{\epsilon/2\Gamma_{\mathrm{p,j}}}^{\infty}\mathrm{d}\epsilon_{\mathrm{j}}\epsilon_{\mathrm{j}}^{-2}\frac{\mathrm{d}n_\gamma(\epsilon_{\mathrm{j}})}{\mathrm{d}\epsilon_{\mathrm{j}}}, \tag{6}$$

where the Lorentz factor of a proton of energy E_{p} is $\Gamma_{\mathrm{p,j}} = E_{\mathrm{p,j}}/m_{\mathrm{p}}c^2$. The threshold energy of pion production in the proton's rest frame is $\epsilon_{\mathrm{th}} = 0.15$ GeV. The cross-section, $\sigma_\pi(\epsilon)$, for pγ → Δ^+ → π^+n in the proton rest frame depends on the photon energy ϵ (also in the proton rest frame). At the resonance peak, this cross-section is 0.5 mb. The average fractional energy, $\xi(\epsilon)$, of a proton going to a pion is 0.2. If this energy is equally shared by the four leptons at the final state, then each positron takes 5 per cent of the parent proton's energy, $E_{\mathrm{e,j}} = 0.05E_{\mathrm{p,j}}$.

The wind expansion time or dynamical time-scale of the jet is $t_{\mathrm{dyn}} = R_{\mathrm{d}}/\delta_{\mathrm{D}}c$, where R_{d} denotes the radius of the emission region in the observer's frame. The fractional proton energy lost to a pion during the dynamical time-scale of the jet is $f_\pi(E_{\mathrm{p,j}}) = t_{\mathrm{dyn}}/t_\pi(E_{\mathrm{p,j}})$ (Waxman & Bahcall 1997). When the dynamical time-scale is comparable to or greater than the pion production time-scale, most of the protons will produce pions in pγ interactions. It is necessary to perform the integration in equation (6) to obtain the expression for $f_\pi(E_{\mathrm{p,j}})$. A simplified expression was given by Waxman & Bahcall (1997), whereas a more general expression involves the spectral indices γ_1 and γ_2 (Gupta & Zhang 2007; Moharana & Gupta 2012).

The break in the low-energy photon spectrum (ϵ_{br}) reflects the break energy in the proton spectrum (E_{pb}), because of the threshold energy condition of pγ interactions $E_{\mathrm{pb}}\epsilon_{\mathrm{br}} = 0.14\delta_{\mathrm{D}}^2$ GeV^2. The synchrotron luminosity, L_γ, is the product of the energy density of the photons and the volume of the emission region per unit time. If the emission is isotropic in the jet frame, then

$$L_\gamma = 4\pi R_{\mathrm{d}}^2\delta_{\mathrm{D}}^2\,Uc. \tag{7}$$

For our purpose, only the energy dependence of $f_\pi(E_{\mathrm{p}})$ is needed.

In terms of the proton energy E_{p} and the break energy in the proton spectrum E_{pb}, which appears because of the break in the low-energy photon spectrum at ϵ_{br}, $f_\pi(E_{\mathrm{p}})$ is (Gupta & Zhang 2007; Moharana & Gupta 2012)

$$f_\pi(E_{\mathrm{p}}) \propto \begin{cases} \left(\dfrac{E_{\mathrm{p}}}{E_{\mathrm{pb}}}\right)^{(\gamma_2-1)}, & E_{\mathrm{p}} < E_{\mathrm{pb}} \\[2ex] \left(\dfrac{E_{\mathrm{p}}}{E_{\mathrm{pb}}}\right)^{(\gamma_1-1)}, & E_{\mathrm{p}} > E_{\mathrm{pb}} \end{cases}. \tag{8}$$

The value of E_{pb} might be reflected in future measurements of the positron spectrum at higher energies.

As mentioned above, in pγ interactions, the probabilities of π^0 and π^+ production are nearly equal. The fractional energy lost by a proton to a pion is $f_\pi(E_{\mathrm{p}})$. Assuming that the energy of π^+ is equally shared by the four leptons at the final state (e$^+$, ν_e, ν_μ and $\bar{\nu}_\mu$), we can write the positron energy flux in terms of the luminosity in protons L_{p}:

$$E_{\mathrm{e}}^2\eta_{\mathrm{p}\gamma\to\nu\mathrm{e}^+}(E_{\mathrm{e}}) = \frac{f_\pi(E_{\mathrm{p}})}{8}L_{\mathrm{p}}. \tag{9}$$

The fraction $f_\pi(E_{\mathrm{p}})$ can also be written as $f_\pi(E_{\mathrm{e}})$ because it contains the ratio of E_{p} and E_{pb}, and $E_{\mathrm{e}} = 0.05E_{\mathrm{p}}$. The flux of positrons per unit energy produced inside the source is $\eta_{\mathrm{p}\gamma\to\nu\mathrm{e}^+}$ (GeV^{-1} s^{-1}) $\propto E_{\mathrm{e}}^{(\gamma_2-3)}$ below the break energy. The spectral index ($\gamma_2 - 3$) is obtained after dividing $f_\pi(E_{\mathrm{e}}) \propto E_{\mathrm{e}}^{(\gamma_2-1)}$ by E_{e}^2. We are considering relativistic positrons with energy larger than 10 GeV, for which synchrotron and synchrotron-self Compton (SSC) losses are important. If the average distance traversed by the electrons and positrons before losing energy is much less than the size of the production region, then the spectrum of the escaping positrons will be steeper by a factor of $1/E_{\mathrm{e}}$ (Berezinskii et al. 1990). Thus, the injected spectrum of positrons from the jets will have a spectrum, $\phi_{\mathrm{p}\gamma\to\nu\mathrm{e}^+}(E_{\mathrm{e}})$ (GeV^{-1} s^{-1}) $\propto E_{\mathrm{e}}^{(\gamma_2-4)}$.

4 DIFFUSED SPECTRUM

The diffusion equation gives the particle density as a function of space, time and energy for a known injection spectrum, diffusion coefficient and energy-loss term (Ginzburg & Syrovatskii 1964; Berezinskii et al. 1990). The energy-dependent diffusion coefficient is $D(E) = D_0E^\delta$, where δ can vary between 0.33 and 0.6 (i.e. the Kolmogorov and Kraichnan models, respectively; Di Bernardo et al. 2010). Synchrotron and inverse Compton (IC) are the most important radiative loss mechanisms for the relativistic electrons and positrons propagating through the Galaxy. Fig. 1 of Jean et al. (2009) has already shown that (even for a warm medium), electrons and positrons with energies in excess of 30 GeV lose energy mainly via synchrotron and IC losses. For GeV electrons and positrons, annihilation in the interstellar medium (ISM) is not important at
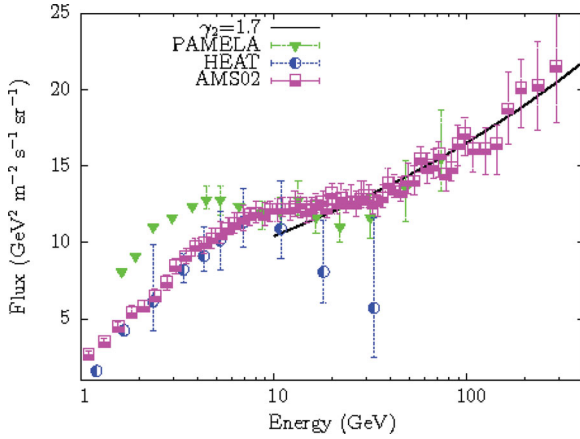
Figure 1. Observed data compared with theoretically obtained positron spectrum in pγ interactions in jets of Lorentz factor $\delta_D = 3$; the solid line denotes $\gamma_2 = 1.7$, $\epsilon_{br} = 0.1$ MeV.

all and can be disregarded. The energy-loss term of electrons and positrons is

$$\frac{dE}{dt} = b(E) = -\beta E^2, \qquad (10)$$

because both synchrotron and IC losses are proportional to E^2, $\beta = 1.38 \times 10^{-16}$ (GeV s)$^{-1}$ (Volkov & Lagutin 2013). Their energy is then $E(t) = E_0/(1 + \beta E_0 t)$, where $E = E_0$ at $t = 0$.

The time taken for the electron or positron of initial energy E_0 to lose half of its energy ($E = E_0/2$) is

$$\tau(E, E_0) = \int_{E_0}^{E} \frac{dE'}{b(E')} = \frac{1}{\beta E_0}. \qquad (11)$$

The average distance to which the particles have diffused while losing energy is (Berezinskii et al. 1990)

$$\lambda(E, E_0) = \left[\int_{E_0}^{E} \frac{D(E') \, dE'}{b(E')} \right]^{1/2}. \qquad (12)$$

Thus, the distance traversed by a 30-GeV positron before losing half of its energy is about 600 pc in a medium with magnetic field of 5 μG and photon density of 1 eV cm^{-3}, assuming $D = 10^{29}$ cm^2 s^{-1}. We consider our Galaxy, with a radial extent of $R \sim 10$ kpc, a disc thickness of $d \sim 150$ pc and a halo size of $h \sim 4$ kpc. If the sources are uniformly distributed in the Galactic disc, then for an injected spectrum $E^{-\alpha}$ the propagated spectrum is proportional to $E^{-\alpha - 1/2}$ for $\lambda(E) > d$ and $E^{-\alpha - 1}$ for $\lambda(E) \ll d$ (Berezinskii et al. 1990). Hence, in our case $\lambda(E) > d$, the propagated spectrum is expected to be $E^{-\alpha - 1/2}$.

In reality, low-mass X-ray binaries (LMXBs) are distributed in the disc, bulge and spheroid of the Milky Way (Bahcall & Soneira 1980; Grimm, Gilfanov & Sunyaev 2002; Revnivtsev et al. 2008) in an approximately 2:1:0.3 ratio. Thus, in principle, it is not necessary to use the distribution of sources from Bahcall & Soneira (1980), also given in equations (4)–(6) of Grimm et al. (2002) to calculate the propagated spectrum of positrons with the transport equation given in equation (5.6) of Berezinskii et al. (1990). Here, we have simplified this problem by assuming a uniform distribution of sources in the Galactic disc.

Under the latter assumption, the observed positron flux is given by equation (5.22) of Berezinskii et al. (1990), which can be further simplified to their equation (5.24):

$$\frac{dN(E)}{dE} \simeq Q(E) c \frac{V_{\text{source}} \tau(E)}{V_{\text{occ}}(E)}. \qquad (13)$$

We have multiplied by c on the right-hand side because the left-hand side has the dimension of GeV^{-1} cm^{-2} s^{-1} sr^{-1} and $Q(E) = KE^{-\alpha}$ is the injected positron density in GeV^{-1} cm^{-3} s^{-1} sr^{-1}. The constant K can be calculated for the volume occupied by the sources V_{source} and the part of the Galaxy occupied by the positrons $V_{\text{occ}}(E)$. In our case, this yields

$$\frac{V_{\text{source}}}{V_{\text{occ}}(E)} = \frac{2\pi R^2 d}{2\pi R^2 \lambda(E)}. \qquad (14)$$

We can calculate the injection positron density required to explain the rise in the positron spectrum beyond 30 GeV with equations (13) and (14). With the required injection positron density, we can then compute the luminosity in positron (and thus proton and gamma-ray) emission required to explain the observed rise.

5 RESULTS AND DISCUSSION

We vary the spectral index γ_2 and the break energy ϵ_{br} to draw a positron spectrum that fits well the rise of the experimental data (see Fig. 1). Assuming interactions in jets of the Doppler factor $\delta_D = 3$, the values of $\gamma_2 = 1.7$ and $\epsilon_{br} = 0.1$ MeV seem to provide a good fit to the experimental data. Our value of 0.1 MeV is similar to the observed peaks in sources such as GX 339–4 (Hannikainen et al. 1998; Homan et al. 2005) and XTE J1118+480 (McClintock et al. 2001; Zurita et al. 2006; Vila et al. 2012). The photon spectrum of spectral index -1.7 is produced from synchrotron emissions of electrons and positrons with a spectrum $[dN_e(E_e)]/dE_e \propto E_e^{-2.4}$. This spectrum is similar to the positron spectrum injected from the jets in our model with a spectral index $\gamma_2 - 4 = -2.3$ as discussed in Section 3. Thus, our model is self-consistent.

Note that from the threshold energy condition of pion production in pγ interactions, if $\epsilon_{br} = 0.1$ MeV (the observer's frame), then the break in the positron spectrum would appear at 630 GeV (also in the observer's frame).

We use equation (13) to calculate $Q(E)$ using the observed positron flux. At $E = 30$ GeV, the observed positron flux is $dN(E)/dE = (12/E^3) \times 10^{-4}$ (GeV^{-1} cm^{-2} s^{-1} sr^{-1}); see Fig. 1. The injection spectrum of positrons is $Q(E)$ (GeV^{-1} cm^{-3} s^{-1} sr^{-1}) $= A/E^{2.3}$ (as for $\gamma_2 = 1.7$, the injected spectral index into the interstellar medium is $\gamma_2 - 4$).

With $d = 150$ pc, $\lambda(E = 30\,\text{GeV}) = 600$ pc $= 1.8 \times 10^{21}$ cm and $\tau(E = 30\,\text{GeV}) = 1/(30 \times 1.38 \times 10^{-16})$ s, we obtain $Q(E) = 6 \times 10^{-29}/E^{2.3}$ (GeV^{-1} cm^{-3} s^{-1} sr^{-1}).

The total volume occupied by the sources $V_s = 2.8 \times 10^{66}$ cm^3 gives, above $E_{\text{min}} = 30$ GeV, the total luminosity in positrons $L_{\text{pos}} = 4\pi V_s \int_{E_{\text{min}}}^{\infty} E \, Q(E) dE = 4 \times 10^{36}$ erg s^{-1}.

Thus, in order to explain the rise in the positron spectrum beyond 30 GeV, the total luminosity injected in positrons from all the LMXBs distributed in the Galactic disc has to be of the order of 10^{36} erg s^{-1}. Note that this is the total luminosity in positrons emitted by all injecting sources in the Galactic disc. If at least hundreds to thousands of such sources are present in the Milky Way with typical Eddington luminosities $\sim 10^{38}$ erg s^{-1} and X-ray luminosities 10^{34}–10^{36} erg s^{-1} (Voss & Ajello 2010), and they emit a positron flux with luminosity $\sim 10^{33-34}$ erg s^{-1} each, then this population of sources, by itself, could explain the rise in the observed diffuse positron flux

above 30 GeV. Probably, although this population contributes to the positron excess, it is not necessarily the only one producing it.

The luminosity distribution functions of the X-ray binaries observed by the *Swift* Burst Alert Telescope (BAT) have been derived by Voss & Ajello (2010), who have found that X-ray binaries give a local emissivity of $2-4 \times 10^{36}$ erg s^{-1} Mpc^{-3} to the X-ray background, of which approximately 80 per cent comes from LMXBs. The incident energy flux from LMXBs in X-rays is $\sim 10^{-11}$ erg s^{-1} cm^{-2} sr^{-1}, which is produced by synchrotron emission from high-energy electrons and positrons inside these sources.

Because the positrons are losing energy before escaping from the site of their production in the jet, the emitted luminosity is lower than their original luminosity. If their luminosity at production were 10 times higher, then we would expect similar luminosity $\sim 10^{34-35}$ erg s^{-1} in gamma-rays and neutrinos from each of these sources. However, distance dilution, beaming and, in the case of photons, absorption would make most of these sources individually undetectable.

The neutrinos produced in pγ interactions do not lose energy inside or outside the jets, unlike positrons. The neutrino spectrum $\phi_\nu(E_\nu)$ (GeV^{-1} s^{-1}) has a spectral index ($\gamma_2 - 3$) below the break at 630 GeV in the observer's frame and ($\gamma_1 - 3$) above, where we assume $\gamma_2 = 1.7$ and $\gamma_1 = 1.5$. At production, the flavour ratio of neutrinos in the jet is $\nu_e:\nu_\mu:\nu_\tau = 1:2:0$, and subsequently, after many oscillations, the observed ratio on Earth is expected to be 1:1:1. For a jet of luminosity of 3×10^{35} erg s^{-1} in neutrinos at a distance of 8 kpc from us and for maximum energy of protons 20 TeV, the muon neutrino flux expected on Earth is calculated below. The neutrino energy flux is enhanced by a factor of $\delta_D^{(2+x)}$ (assuming the jets are continuous) in the observer's frame (Ghisellini et al. 1993) as a result of Doppler boosting, where x is its spectral index. The muon neutrino energy flux is expected to be $E_{\nu_\mu}^2 \phi_{\nu_\mu}(E_{\nu_\mu}) = 1.7 \times 10^{-10} E_{\nu_\mu}^{0.7}$ GeV cm^{-2} s^{-1} and $E_{\nu_\mu}^2 \phi_{\nu_\mu}(E_{\nu_\mu}) = 6 \times 10^{-10} E_{\nu_\mu}^{0.5}$ GeV cm^{-2} s^{-1} below and above the break energy at 630 GeV, which is much lower than the atmospheric neutrino background.

A more detailed study in which the sources are not uniformly distributed, and/or they do not present the same injection features, would allow us to determine whether this explanation can deal with the whole or part of the positron fraction.

6 CONCLUDING REMARKS

The recent detection of Doppler-shifted X-ray emission lines from a typical black hole candidate X-ray binary, 4U 1630–47, coincident with the reappearance of radio emission from the jets of the source, implies that baryons can be accelerated in jets of microquasars (Díaz Trigo et al. 2013). The jets should be strong sources of gamma-rays and neutrinos, and in principle could contribute to the observed positron excess significantly.

The positron excess has been studied earlier with pp interaction models (e.g. Gaggero et al. 2014), and constrained with observed B/C ratios (e.g. Cholis & Hooper 2014; Mertsch & Sarkar 2014). Here, we have shown that pγ interactions in boosted environments, such as the jets of microquasars, can help to explain the observed rise in the positron spectrum beyond 30 GeV. Low-mass microquasars are of special interest in this regard, because hadronic models based on inelastic pp collisions are not expected to play a leading role, the companion star being cold and old. For the same reasons, the external photon background is scarce, which would limit (albeit not rule out in all cases, especially due to SSC; e.g. Bosch-Ramon

et al. 2006a; Bosch-Ramon, Romero & Paredes 2006b) the ability of leptonic processes to dominate the spectra. If jets accelerate protons, these sources might lead to multiparticle injection via pγ processes, where perhaps the photons are synchrotron-generated at the base of the jets (e.g. Levinson & Waxman 2001). For recent models of proton low-mass microquasars, see Romero & Vila (2008), Vila & Romero (2010), Saitou et al. (2011), Zhang et al. (2010) and Vila et al. (2012). Luminosities of the pγ channel in these works for individual sources are in agreement with the requirements found in our work needed to explain a significant part of the positron excess with microquasar jets.

Finally, we compare our scenario of pγ interactions and subsequent photo-pion decay with the scenario of cosmic ray interactions in the interstellar medium, as discussed by Cowsik, Burch & Maziwa-Nussinov (2014). They have interpreted the observed positron spectrum as secondaries produced in interactions of primary cosmic ray nuclei with the interstellar medium, assuming that the positrons remain in the Galaxy for 2 Myr. According to their prediction, the positron spectrum is proportional to $E_e^{-3.65}$ above 300 GeV. In our case, the spectrum is proportional to $E_e^{-2.8}$ up to the break energy in the positron spectrum at 630 GeV, if the break energy ϵ_{br} in the synchrotron spectrum of photons from the jets is at 0.1 MeV. Above the break energy, the spectral index of the positron spectrum would be proportional to $E_e^{\gamma_1 - 4 - 1/2}$, where γ_1 is the spectral index of the photon spectrum below ϵ_{br}. In some cases, the positron flux from these sources could be higher than their electron flux, for instance, if their luminosity in primary protons is higher than in electrons. If so, we expect these sources to be positron-dominated and not to contribute significantly to the observed diffuse electron flux.

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