Neutrino astrophysics

The Fermi acceleration of electrons producing the observed **GRB** or AGN γ-ray, X-ray and optical photons is likely also to accelerate protons, either in internal shocks [1] or external shocks [4]. The extreme electromagnetic brightness implies a high intra-source density of photons, and a high optical depth to $p\gamma$ photo-meson interactions. Interactions between protons of $E_p \gtrsim 10^{16}$ eV and photons of ϵ_γ leads to neutrinos whose energy in the observer frame is $E_{\nu,\,\mathrm{GeV}} \sim 10^{-2}\Gamma^2/\epsilon_{\gamma,\,\mathrm{GeV}} \sim 100$ TeV and extending to PeV for a GRB emitting MeV photons from a jet of Lorentz factor $\Gamma \sim 10^2$. A comprehensive discussion of Fermi acceleration and neutrinos in GRBs and AGNs was given in [3].

A different mechanism for neutrino production in GRB [6] is inelastic p, n collisions in the outflow, caused by the relative drift between entrained neutrons and protons when they decouple; these neutrinos have energies $E_\nu \sim 40-50$ GeV. Another neutrino component [7] is expected from core-collapse "long" GRBs, when internal shocks occur while the jet is still inside the star. Photo-meson and pp neutrinos at $E_\nu \sim 1$ TeV arise then as precursors $\sim 10-100$ s before the γ-rays from the post-emergence jet. There may be a large number of 'failed' GRB, where **choked jets** did not emerge, leading to an orphan neutrino burst [7] without a corresponding electromagnetic signal. Neutrinos would serve as 'tomographical' probes of the stellar structure of the stellar progenitors [8]. More detailed predictions for choked and sub-photospheric jet neutrinos were given in [9], and a different, proton-neutron converter mechanism for neutrino production in buried radiation-dominated flows was discussed in [10].

The shocks in the jets of **AGNs** may also be photo-meson neutrino sources. However, there are many more AGNs with modest or no jets, and the cores of such 'radio-quiet' AGNs may be promising neutrino sources. This is due to shocks between blobs in the inner accretion flow or the incipient jets near the central black hole [11, 12]. **Hypernovae**, or jet-powered supernovae, are core-collapse supernovae exhibiting semi-relativistic ejecta velocities, and these can accelerate protons or ions to relativistic energies leading to GeV to PeV neutrinos [13, 14]. **Magnetars** are ultra-high magnetic field ($\gtrsim 10^{14}$ Gauss) neutron stars, which give rise to soft-gamma repeaters (SGRs), burst-like events due to magnetic reconnection leading to a fireball where shocks Fermi accelerate electrons as well as protons, which can lead to photo-meson neutrinos [15] or curvature radiation neutrinos [16]. In newly formed magnetars, wake-field acceleration can accelerate protons which interact with the SN ejecta leading to significant neutrino fluxes [17].

The diffuse TeV-PeV neutrino background observed by *IceCube*, e.g. [18], appears to be due to so-far unidentified sources at cosmological distances. Since $p\gamma$ and pp interactions produce both VHE neutrinos and γ-rays comparable numbers, the diffuse γ=ray background observed by the *Fermi* satellite imposes a strong constraint, since the latter is largely due to blazars, which however do not correlate with the neutrinos. Most optically thin sources would overproduce γ-rays, but γ-ray-dark sources such as low-luminosity or choked GRBs [19], or shocks from high-redshift merging galaxies and clusters [20] are likely sources which satisfy the constraints. A wider discussion is given in a recent review [21].

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