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Neutrino Bursts from Fanaroff-Riley I Radio Galaxies

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On the basis of existing observations (at the 4.5 σ level) of TeV γ-ray outbursts from the Fanaroff-Riley I (FRI) radio galaxy Centaurus A, we estimate the accompanying neutrino flux in a scenario where both photons and neutrinos emerge from pion decay. We find a neutrino flux on Earth $dF_\nu/dE_\nu = 4.5\times10^{-11}\ (E_\nu/\text{TeV})^{-2}\ \text{TeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}$, equally spread in flavor as a result of maximal mixing. Such a flux will trigger at the IceCube facility about 10 showers/burst, with negligible background from atmospheric muons, and primary neutrino energies in excess of 100 TeV. The only other FRI radio galaxy observed in the TeV photon energy range at the 4σ level is M87. The burst nature of this activity is not established; however, we show that the intrinsic neutrino luminosity during the active period is the same as the Centaurus A burst. On the assumption that Centaurus A typifies the FRI population, we show that IceCube should collect 10 showers (all neutrino flavors) in 3 years, attaining a 95% CL sensitivity to the diffuse neutrino flux from FRI radio galaxies in one year of observation.

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Conventional astronomy spans about 18 decades in photon wavelengths, from 10^4 cm radio-waves to 10^{-14} cm γ-rays of GeV energy. Because the universe is opaque to photons of TeV energy and above, present studies focus on hadrons, neutrinos, and gravitational waves as messengers probing the high energy universe. The best candidates to serve as messengers in a new astronomy of the high energy behavior of distant sources are neutral particles. This is because the orbit of a charged cosmic ray can be substantially bent by the ambient magnetic field of our own galaxy, destroying the possibility of locating the source. The most promising messenger is the neutrino: it can be copiously produced in cosmic beam dumps and can traverse unscathed dense astrophysical environments. In this context, we recently carried out a study of directional neutrino signals from sources in the Galactic plane [1]. In this letter we extend this project to the extragalactic domain, and delineate the prospects to identify Fanaroff-Riley I (FRI) radio galaxies as high energy neutrino emitters. In our discussion it will be seen explicitly how the neutrinos provide a signal precisely where photon signals are blocked by interactions with the universal radiation backgrounds permeating the universe.

At present, a handful of sources have been established as TeV γ-ray emitters [2]. All of them are nearby BL Lac objects characterized by strong rapid variability and apparent superluminal motion. These extreme features are generally interpreted as a consequence of dissipative effects (non-thermal emission) from a relativistic jet oriented at small angle with respect to the line-of-sight [3].

There are two principal mechanisms for TeV gamma ray production: *(i)* Electrons undergo bremsstrahlung in the magnetic field and/or inverse Compton scattering in the ambient photon sea or *(ii)* the gamma rays are directly traced to π^0 decay. Only the second scenario can accommodate baryonic cosmic ray production. Since such cosmic rays are observed, it is reasonable to assume that at least some gamma ray sources operate according to the second mechanism.

In the context of unification models [4], BL Lac objects are intrinsically the same as FRI. Though the jet emission from FRIs is not strongly Doppler boosted towards us (and may even be de-boosted), in some cases the lack of relativistic boosting can be partially compensated by proximity to Earth. Therefore, some FRI radio galaxies could be detectable in the TeV range. In what follows, we examine the consequences of assuming that gamma ray emission from FRI originates in π^0 decay, and is necessarily accompanied by a flux of high energy neutrinos emerging from the $\pi^\pm$ population.

At a distance of 3.4 Mpc, Centaurus A (Cen A) is the prototype of FRI galaxies [5]. It is the only GeV gamma ray source with a confirmed large-inclination jet [6]. Data collected in the early 70's with the optical intensity interferometer operated by Sydney University at Narrabri, show a $\sim 4.5\sigma$ (time average) excess of γ-ray events from the direction of Cen A [7]. The reported cumulative flux averaged over 3 yr of observations is

$$F_\gamma(E_\gamma > 300\ \text{GeV}) = 4.4 \pm 1.0 \times 10^{-11}\ \text{cm}^{-2}\ \text{s}^{-1}\,. \quad (1)$$

Based on a power-law spectrum $\propto E_\gamma^{-2}$, this corresponds to a luminosity at the source of $\mathcal{L} \approx 7.5 \times 10^{40}$ erg s^{-1}. It is important to note that since the detector beam did not include the radio lobes, it is likely that the source resides in the compact nucleus of Cen A. The data reveals two different periods of heightened activity in the TeV range, each of about 1 year duration. Though data at the upper end of the spectrum await confirmation, the γ-ray bandwidth of Cen A could reach energies as high as hundreds of TeV. There are specific hints in this direction in data reported during the 1980's and 1990's by the Buckland [8] and JANZOS [9] collaborations. Several items can be noted with respect to these measurements: *(i)* The data are consistent with bursts of approximately one year duration every decade. *(ii)* Both experiments reveal an upper cutoff of ~ 200 TeV, which can be ascribed to absorption on the background radiation fields. *(iii)* The reported flux in both cases is about 2 orders of magnitude larger than that measured at the Narrabri Observatory; the chance probabilities are 6×10^{-3} and 2×10^{-2} for Buckland and JANZOS, respectively. Although these data are not at the discovery level, the observations of 100-TeV photons at the two facilities corroborate one another. *(iv)* The emission of 100-TeV gamma rays is supportive of their origin in pion production and decay processes, as opposed to synchrotron and inverse Compton scattering [10].

Additional relevant information about the source is contained in these observations. The $\sim$ 1-year duration of the observed burst at Narrabri implies a coherent region of activity $r \sim 0.3$ pc. Therefore, the recent discovery of a sub-parsec radio counterjet in the nucleus of Cen A is of interest [11]. As a conservative estimate we adopt the flux in Eq.(1) as the photon excess characterizing the Cen A burst, which corresponds to an integrated burst energy $E_{\rm burst} = 2.3 \times 10^{48}$ erg.

A high-energy neutrino flux emerges if the charged pion decay length is smaller than the pion interaction length in the source region. The latter, as well as the pion production rate, depends on the gaseous hadronic particle density. An estimate of the target nucleons can be obtained by assuming that the gas density n near the accretion disk of the supermassive black hole engine of Cen A is similar to that near the center of our Galaxy. This in turn is arrived at by assuming that the gas/star density ratio near the center is the same as the one in the Galactic disk, yielding $n \approx 10^6$ cm^{-3}. Our estimate is most likely a lower bound on the gas density, since the Cen A black hole mass $M_{\rm BH} \approx 2 \times 10^8\ M_\odot$ [12] is about 2 orders of magnitude greater than SgrA* [13, 14]. With this in mind, the corresponding pion mean free path $(n\sigma_{\pi N})^{-1} \approx 6.5$ pc is much greater than the charged pion decay length, which at 100 TeV is 5.6×10^8 cm. (Here $\sigma_{\pi N} \approx 50$ mb is the pion-nucleon cross section.) On the other hand, the mean free path for collision of the ultrarelativistic accelerated protons on the gas is $(n\sigma_{pN})^{-1} \approx 4.6$ pc, where $\sigma_{pN} \approx 70$ mb [15]. Assuming no significant deflections on the magnetic field, this implies a probability of interaction in the coherent region $p = r\ n\ \sigma_{pN} \approx 7\%$. The infalling mass $M_{\rm infall}$ required to power the burst is found through the relation

$$E_{\rm burst} = p\, G\, M_{\rm BH}\, M_{\rm infall}/r_s\ , \tag{2}$$

where G is Newton's constant and r_s is the Schwarzschild radius. This gives $M_{\rm infall} \approx 3.6 \times 10^{-5}\ M_\odot$. This is about 100 times larger than the estimated infall rate for the Galactic black hole [16]. Because of the burst nature, coupled with the much larger mass for the Cen A black hole, we take this as a reasonable accretion rate, allowing sufficient pion production.

Since π^0's, π^+'s, and π^-'s are made in equal numbers, one expects two photons, two ν_e's, and four ν_μ's per π^0. On average, the photons carry one-half of the energy of the pion, and the neutrinos carry one-quarter. The energy-bins dE scale with these fractions, and we arrive at

$$\begin{aligned} \frac{dF_\gamma}{dE_\gamma}(E_\gamma = E_\pi/2) &= 4\,\frac{dF_\pi}{dE_\pi}(E_\pi)\,, \\ \frac{dF_{\nu_e}}{dE_{\nu_e}}(E_{\nu_e} = E_\pi/4) &= 4\,\frac{dF_\pi}{dE_\pi}(E_\pi)\,, \\ \frac{dF_{\nu_\mu}}{dE_{\nu_\mu}}(E_{\nu_\mu} = E_\pi/4) &= 8\,\frac{dF_\pi}{dE_\pi}(E_\pi)\,, \end{aligned} \tag{3}$$

for the fluxes at the source, where π denotes any one of the three pion charge-states. Terrestrial experiments (see e.g. [17]) have shown that ν_μ and ν_τ are maximally mixed with a mass-squared difference $\sim 10^{-3}$eV^2. This together with the known smallness of $|\langle \nu_e | \nu_3 \rangle|^2$, implies that the ν_μ's will partition themselves equally between ν_μ's and ν_τ's on lengths large compared to the oscillation length $\lambda_{\rm osc} \sim 1.5 \times 10^{-3}\,(E_\nu/{\rm PeV})$ pc. Here $\nu_3 \simeq (\nu_\mu + \nu_\tau)/\sqrt{2}$ is the third neutrino eigenstate. From these remarks, one finds a nearly identical flux for each of the three neutrino flavors $(j = e, \mu, \tau)$, which is equal to

$$\frac{dF_{\nu_j}}{dE_{\nu_j}}(E_{\nu_j} = E_\gamma/2) = 2\frac{dF_\gamma}{dE_\gamma}(E_\gamma)\,. \tag{4}$$

On the assumption of an E_γ^{-2} spectrum, we fix the normalization using the cumulative number flux of Eq. (1) with an upper cutoff at 3 TeV [7]. From Eq. (4) we then obtain the neutrino flux on Earth

$$\frac{dF_{\nu_j}}{dE_\nu} = 1.5 \times 10^{-11}\ \left(\frac{E_\nu}{\rm TeV}\right)^{-2}\ {\rm TeV}^{-1}{\rm cm}^{-2}{\rm s}^{-1}\,. \tag{5}$$

The observation of 100-TeV photons supports the extrapolation of the spectrum in Eq. (5) to those high energies.

The most promising prospect for detection of such a low flux is the IceCube facility under construction at the South Pole [18]. For energies above ~ 100 TeV, IceCube will provide 4π detection of neutrinos since the atmospheric muon flux is negligible. Moreover, at these energies the telescope will be able to resolve directionality in all neutrino flavors. The total number of showers in a single burst of duration $t \simeq 1$ yr is then

$$\mathcal{N}_{\rm IceCube} = N_A\ \ \rho\ t\ V_{\rm eff}\ \sum_j \int_{E_{\nu,\rm min}}^\infty \frac{dF_{\nu_j}}{dE_\nu}\ \sigma_{\nu N}^{\rm CC}\ dE_\nu\ , \tag{6}$$

where N_A is Avogadro's number, $V_{\rm eff} \approx 2$ km^3 is the effective volume of ice with density ρ, and $\sigma_{\nu N}^{\rm CC} = 6.78 \times 10^{-35}\,(E_\nu/{\rm TeV})^{0.363}$ cm^2 is the charged current neutrino-nucleon cross section [19]. By substituting the flux given in Eq.(5), we find about 10 showers per burst, with primary neutrino energy > 100 TeV. Thus we arrive at the first prediction of this paper: *during a burst similar to the 4.5σ event detected by the Narrabri Observatory, IceCube will detect about one 100-TeV neutrino per month pointing to Cen A. This signal persists even in the absence of the emitted photons which are absorbed on the infrared and microwave radiation backgrounds.*

Located in the Northern hemisphere at a distance of 16 Mpc, M87 is the FRI with the brightest optical jet [20]. It shows most of the characteristics of BL Lac objects, with the jet oriented at $30° - 35°$ to our line of sight. Data taken during 1998-1999 with the HEGRA stereoscopic system of 5 imaging atmospheric Čerenkov telescopes show an excess of photons from the direction of M87 with significance level 4.1σ above background [21]. The observed cumulative flux is

$$F_\gamma(E_\gamma > 730\ \mathrm{GeV}) = 0.96 \pm 0.23 \times 10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\,. \quad (7)$$

The data can be fit with a power law $dF_\gamma/dE_\gamma \sim E_\gamma^{-\alpha}$, with $\alpha = 2.9 \pm 0.8_{\rm stat} \pm 0.08_{\rm syst}$. The large uncertainty in the spectral index is not, however, reflected in obtaining the source luminosity: with an upper cutoff of 5 TeV, there is about a 25% variation as α varies between 2 and 2.9. Hereafter, we take $\alpha = 2$ to reflect the conventional Fermi engine emission spectrum. This corresponds to a γ-ray luminosity at the source $\mathcal{L} \approx 6.8 \times 10^{40}$ erg s^{-1}. This is remarkably close to the γ-ray source luminosity of the Cen A burst obtained above.

By duplicating for M87 our Cen A discussion, we obtain

$$\frac{dF_{\nu_j}}{dE_\nu} = 7 \times 10^{-13}\ \left(\frac{E_\nu}{\mathrm{TeV}}\right)^{-2}\ \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\,. \quad (8)$$

A rough estimate of the event rate at IceCube can be obtained following the analysis of our previous paper [1]. Using the terrestrial transmission probability given in [22], and a conservative effective area of 1 km^2, we find about 2 events/yr during a period of TeV gamma ray activity. This is similar to the ν_μ atmospheric background. A more definitive assessment of sensitivity to such a signal will await further refinement of angular and energy resolutions via improved knowledge of the detector response. Additionally, the temporal profile of future gamma ray observation will allow a better delineation of the signal.

Although there are no other nearby FRIs of this magnitude which can potentially be detected as point sources, one can integrate over the estimated FRI population out to the horizon to obtain a prediction for the diffuse neutrino flux. This quantity is given by

$$J_\nu(E_\nu) = \frac{1}{4\pi}\ \mathcal{R}\ n_{\rm FRI}\ \mathcal{L}_\nu \quad (9)$$

where $\mathcal{R} \simeq 1$ horizon $\simeq 3$ Gpc, $n_{\rm FRI} \sim 8 \times 10^4$ Gpc^{-3} is the number density of FRI [23], and $\mathcal{L}_\nu = (dN_0/dE_\nu)/\tau$ is an average neutrino luminosity (all flavors) of FRI radio galaxies. Here dN_0/dE_ν is the differential injection spectrum for a single burst and $\tau \sim 10$ yr is the period between outbursts. Although the burst nature of the HEGRA observation is not established, in what follows we conservatively assume that the photon excess from M87 is localized to an outburst period. Since both Cen A and M87 have almost the same luminosity, we adopt this as the average for FRI radio galaxies. Thus, the quantity dN_0/dE_ν can be obtained from Eq. (5),

$$\frac{dN_0}{dE_\nu} = 4\pi d^2\ N_f\ t\ \frac{dF_{\nu_j}}{dE_\nu} \quad (10)$$

where $N_f = 3$ is the number of neutrino flavors and d is the distance to the source. For long time averages we find

$$\frac{1}{\tau}\ \frac{dN_0}{dE_\nu} = 5.7 \times 10^{39}\ E_\nu^{-2}\ \ \mathrm{TeV}^{-1}\,\mathrm{s}^{-1}\,. \quad (11)$$

The diffuse flux observed on Earth then follows from Eq. (9)

$$E_\nu^2\ J_\nu \simeq 1.2 \times 10^{-11}\,\mathrm{TeV\ cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\,. \quad (12)$$

Note that this flux is about a factor of 2 smaller than the Waxman-Bahcall [24] upper limit on the intensity of neutrinos produced in sources which also emit baryonic cosmic rays. After 3 years of observation, the 90% CL sensitivity (corresponding to 2.44 events) of IceCube to the diffuse muon neutrino flux is $E_\nu^2\ J_{\nu_\mu} \simeq 3 \times 10^{-12}\,\mathrm{TeV\ cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ [18]. We arrive then at the second prediction of this work: *If the observations of Cen A at Narrabri and HEGRA measurements of M87 characterize the outburst of FRI radio galaxies, then IceCube will collect about 10 neutrino events (all flavors) in three years.*

It seems worthwhile to briefly examine the implications of neutrino bursts of magnitude corresponding to the γ-ray intensities reported by the Buckland and JANZOS collaborations, with full knowledge that these observations are not at the discovery level. Such a powerful burst implies a neutrino flux on Earth about 2 orders of magnitude greater than that in Eq. (5). In addition to vastly increasing the event rate at IceCube, the ν_μ flux should be detected by 0.1 km^2 neutrino telescopes under construction (ANTARES [25], NESTOR [26]) and a planned 1 km^3 facility [27], all in the Mediterranean. The location of ANTARES at 43° North provides a 5σ discovery sensitivity of $1.2 \times 10^{-10}\ (E_\nu/\mathrm{TeV})^{-2}$ TeV^{-1} cm^{-2} s^{-1} (for muon neutrinos) in the direction of Cen A [28]. We find that in the course of ~ 10 years of observation, ANTARES and NESTOR will measure a neutrino burst an order of magnitude larger than the 5σ detector sensitivity.

In summary, we have analyzed the possibility of detecting the neutrino counterparts of various TeV γ-ray observations in a model where gamma rays originate through π^0-decay at the source. We have found that Icecube will attain sensitivity to observe neutrino bursts from Cen A. Moreover, if the γ-ray observations with the Narrabri Observatory and the HEGRA Čerenkov telescopes characterize the emission behavior of the FRI population, then

IceCube should observe the diffuse ν_μ flux with statistical significance in several years. In light of this, we conclude that observations at future neutrino telescopes will permit a major advance in discriminating between high energy astrophysical processes.

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