Cosmic ray astrophysics

Cosmic rays (CRs) below 10^{15} eV are thought to be Fermi accelerated in supernova remnant shocks, but the origin of CRs above that and up to the 'GZK' limit $E \lesssim 10^{20}$ eV is debated. A steepening of the diffuse spectrum attributed to the GZK process (interaction with CMB photons) has been observed by the Auger observatory [1], and the sources appear to be inside $R_{GZK} \lesssim 50 - 100$Mpc. There are no significant spatial correlations with any type of sources, in particular AGNs, and the chemical composition of the UHECR ($10^{17} - 10^{21}$ eV) become increasingly dominated by elements in the C, O and heavier mass range [2]. These observations strongly favor an astrophysical, as opposed to a 'new physics', origin and the question is what are these sources.

AGNs, in particular luminous radio-loud (jetted) AGNs have long been considered candidates [3], but there are too few of these inside R_{GZK}. More promising is that acceleration occurs in **radio-quiet AGNs**, [4], which may provide acceleration sites with the right properties in large enough numbers. The challenge is in explaining both the spectrum and the heavy element composition [2].

GRB are another main candidate [5, 6]. These are transient, and taking into account diffusion time delays, they occur at a sufficient rate inside R_{GZK} [7]. The maximum energy of protons achievable, both in AGNs and GRBs, is the GZK value $E_p \lesssim \beta_s ZeBR \sim 10^{20.5}$ eV. In GRB the proton number spectrum expected has slope -2, which is suitable for explaining the diffuse CR flux in the $10^{19} - 10^{21}$ eV range. Proof, however, is difficult. Neutrinos from $p\gamma$ at these GZK energies would have $E_\nu \sim 10^{18}$ eV, which requires larger instruments, e.g., ANITA, but the lower energy CRs would be connected to neutrinos in the IceCube range, $10^{12} - 10^{16}$ eV. The IceCube team [8] compared four years of observations against three GRB models, including the standard (time-independent) internal shock at constant radius, and concluded that less than 1% of classical (high luminosity) GRBs could be responsible for the neutrinos. However, a time-dependent calculation of GRB internal shocks producing gamma-rays, cosmic rays and neutrinos, allowing for the radial expansion, shows that in classical GRBs internal shocks can produce much of the $10^{19} - 10^{21}$ eV CRs, without violating the IceCube limits [9]. Alternatively, if the GRB γ-rays arise in a different region (say the photosphere) than the shocks which accelerate the protons, a detailed calculation shows that the Auger GZK spectrum can be explained in the $10^{19} - 10^{21}$ eV range with classical GRBs without violating the IceCube non-detection [10].

At energies below $\sim 10^{18} - 10^{19}$ eV the CR -2 spectral slope is flatter than the observed -2.7, and either longer diffusion times from nearby GRB [11], or other types of sources must be invoked. The latter may be **hypernovae** [12], supernovae with semi-relativistic ejecta, which can accelerate protons up to 10^{19} eV or heavy nuclei up to $10^{20.5}$ eV. The numbers and the inferred distribution of ejecta velocities yield the appropriate spectrum and diffuse flux, and heavy elements can be accelerated and survive as well [12].

Another possible source for the UHECR spectrum and the heavy composition in the $10^{18} - 10^{21}$ eV range is provided by **low-luminosity GRBs**. A detailed calculation of the entrainment of metals from the LLGRB stellar progenitor cores, the acceleration and the propagation through intergalactic space using the GalProp code gives good agreement with the both the spectrum and composition as measured by X_{max} and $\sigma(X_{max})$ [13].

References

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