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Searching for Strangelets and Macro-SQM Candidates from Neutron Stars, Binary Mergers, and Gamma-Ray Bursts: Multi-messenger Constraints and Direct-Detection Prospects

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Strange quark matter (SQM) is a compelling candidate for the true ground state of quantum chromodynamics (QCD) at high baryon density. Within the Bodmer-Witten-Terazawa hypothesis, if SQM has a lower energy per baryon than ordinary hadronic matter, neutron stars can convert to strange quark stars (SQSs). Stable clusters of SQM, strangelets, can be produced in dense QCD phase transitions, releasing up to $\sim 10^{53}$ erg. Strangelets consist of approximately equal numbers of up, down, and strange quarks; their baryon number A is one third of the total quark number, and their net electric charge is Z . Both MIT-bag and Nambu-Jona-Lasinio descriptions predict mass-to-charge ratios $m_S/|Z| \sim 30$ to 60 GeV/ c^2 for $A \sim 10^2$ to 10^5 . A key formation channel is the transition from the two-flavor color-superconducting (2SC) phase to the color-flavor-locked (CFL) phase in dense quark matter. Diquark condensation, fragmentation of Fermi surfaces, and surface emission of quark clusters can produce strangelets, while strangelet-anti-strangelet annihilation, $S\bar{S} \rightarrow \gamma\gamma$, can generate narrow, monochromatic very-high-energy (VHE) γ -ray lines.

This work develops a unified framework connecting QCD-motivated strangelet production to observable multi-messenger fluxes. A phenomenological production-rate model is introduced that balances geometric growth, $\dot{N}(A) \propto (A/A_{\text{peak}})^{2/3}$, against exponential suppression from multi-fragmentation and coalescence. The framework is applied to three representative astrophysical environments: (i) HESS J1731–347, a steady SQS candidate with $M = 0.77^{+0.20}_{-0.17} M_{\odot}$ and $R = 10.4^{+0.86}_{-0.78}$ km, whose 2SC-CFL interface can inject strangelets into the surrounding supernova remnant; (ii) GW170817, the first binary neutron-star merger, where the hadron-to-quark transition in the post-merger remnant can produce a burst-like strangelet flux; and (iii) GRB 250702B, an ultra-long gamma-ray burst with duration $> 25,000$ s and $E_{\text{iso}} > 1.4 \times 10^{54}$ erg, providing an extreme burst-driven channel. Constraints from H.E.S.S., Fermi-LAT, MAGIC-II, and the projected Cherenkov Telescope Array (CTA) are compiled. The baseline scenario lies near the CTA sensitivity threshold ($\sim 10^{-13}$ ph cm $^{-2}$ s $^{-1}$ at 1 TeV); the optimistic scenario is already excluded by H.E.S.S., while the conservative scenario requires next-generation instruments.

A complementary direct-detection program targets macroscopic SQM composites such as nuclearites and Q-balls. Although microscopic strangelets are unlikely to survive interstellar propagation, these heavier objects possess extremely large mass-to-charge ratios and high ionization densities, allowing them to traverse the interstellar medium and penetrate the terrestrial atmosphere. Their passage would produce bright, continuous high-ionization tracks, thermal shock fronts, and slow luminous transits in large-volume detectors. Existing limits from MACRO, SLIM, ANTARES, and IceCube already constrain parts of the parameter space, while future facilities including LHAASO, KM3NeT/ARCA, SQM-ISS, and gravitational-wave observatories will provide complementary sensitivity. Combining narrow VHE γ -ray line searches with direct macro-SQM detection and multi-messenger follow-up of neutron stars, mergers, and GRBs offer a decisive test of the strange quark matter hypothesis.

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