Snowmass2021 - Letter of Interest

Fundamental Physics with Magnetars

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics

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Abstract: Fundamental aspects of quantum electrodynamics (QED) in external fields remain beyond the reach of tests in terrestrial experiments. These include the polarization of the quantum vacuum by electromagnetic fields, associated creation of electron-positron pairs and non-conservation of 3D momentum in strongly magnetized environs, and the exotic process of the splitting of photons in two. Neutrons stars provide viable cosmic laboratories for probing this physics, principally through the detection of spectral and polarization signatures in their X-ray and gamma-ray emission. A next generation of Compton and pair conversion telescopes that improve hard X-ray MeV-band detection sensitivity by more than a decade beyond current instrumental capabilities will open up new insights into a variety of astrophysical source classes. Among these are magnetars, the most highly magnetic of the neutron star zoo, which will serve as a prime science target for a new mission surveying the MeV window.

Introduction and Context

Neutron stars serve as useful laboratories to study physics under conditions of extreme density, gravity, and magnetic fields inaccessible terrestrially. Magnetars represent a topical subclass of the neutron star family which possess the highest magnetic fields in the Universe, with surface and internal values exceeding $B_p \sim 10^9 - 10^{12}$ Tesla. It is crucial to recognize that such fields are in the QED domain where $\hbar\omega_B \sim m_e c^2$ ($\hbar\omega_B$ the energy scale of electron Landau states). This defines the Schwinger or critical field $m_e^2 c^3/(\hbar q_e) \equiv B_{\rm cr} \approx 4.413 \times 10^9$ T and is a regime where exotic aspects[1;2] of standard (but nonlinear and nonperturbative) QED are important as well as possibly beyond standard model physics associated with new particles (e.g. axions) which may couple to intense fields.

Despite the relatively low number of local magnetars (23 confirmed, 6 candidates), they possess an enormous topicality, as evidenced by the shear number of dedicated reviews in recent years years[3–8]. The output of nearby magnetars is largely observed through their X-ray/γ-ray emission via bursts and persistent signals. Nearby magnetars could be a possible source of high-energy neutrinos from charm hadrons[9], possibly observable by POEMMA, Ice Cube-Gen2 and GRAND. Recently, magnetars have also been implicated[10–14] in the mysterious extragalactic Fast Radio Bursts (FRBs)[15] with associated hard X-ray bursts. Strong-field processes, particularly single photon pair creation, also likely play a role[16–19] in the physics associated with FRBs. In passing we note that FRBs offer the exciting prospect as tools to constrain cosmological models[20–30], complimentary to existing methods. It is anticipated thousands of FRBs will be detected in the coming decade. Although this LoI's focus is on the γ-ray aspect of magnetars from concepts such as AMEGO[31], we encourage CF conveners to solicit contributions from the FRB radio community.

Soft Gamma-Ray Phenomenology of Magnetars

Magnetars spend much of their time in a quiescent state, where they are observed as persistent quasi-thermal hot X-ray emitters with $kT \sim 0.5$ keV. They occasionally enter burst active episodes where they emit a few to hundreds of short ($\lesssim 0.1 - 1$ s), bright bursts in the 5–500 keV band, consistent with Comptonized fireball photospheres at relatively low altitude. One of these bursts was recently associated with an FRB[10–14] although it is important to note only some bursts (perhaps spectrally special) seem to produce FRBs[32] which could be constrained by future simultaneous observations in the hard X-rays and radio.

Some magnetars also exhibit persistent pulsed nonthermal hard X-ray continuum emission. Moreover, this component may be energetically dominant, with fluxes exceeding that of the soft components, often by factors of 10 or more. These hard power laws do not exhibit a break below $100 - 200$ keV, and in a few cases, *INTEGRAL*, CGRO-COMPTEL and *Fermi*-LAT upper limits at energies $300 - 1000$ keV imply that a break must exist in this soft γ-ray energy band. The nonthermal nature of the persistent hard X-ray tails suggests that they are powered by a relativistic electron/positron population. In contrast to normal pulsars, the persistent emission likely arises in the "closed" zone of the magnetosphere where particle acceleration proceeds in a magnetosphere that departs from ideal force-free magnetohydrodynamics. A quasi-equilibrium is established where particle acceleration, pair production and radiative losses are in counterbalance[33;34].

At low altitudes where emission likely originates, *resonant inverse Compton scattering (RICS)* of the soft thermal surface photons is the dominant radiative process for electrons that is germane to the generation of hard X-ray tails[35–42]. The scattering cross section is greatly enhanced at the cyclotron fundamental, where the incoming photon energy is equal to the gyroenergy $\hbar\omega_B$ in the electron rest frame. Rapid cyclotron cooling restricts electrons to move parallel to the field. Strong Doppler beaming anisotropy and flux (and photon energy) boosting then result from RICS, which is imprinted on light curves, and traces the field geometry (electron motion) and locales of the particles acceleration and cooling. RICS produces a relatively flat spectrum, with high linear polarization degree, which cuts off at a kinematically determined energy[42].

Magnetar magnetospheres are also opaque for hard X-rays and γ rays. The measured spectral cutoffs may also be produced by attenuation of photons principally due to *magnetic photon splitting* ($\gamma + B \to \gamma\gamma$)

and *pair production* ($\gamma + B \rightarrow e^+e^-$). These exotic QED propagation effects[2;16;43;44] which are as yet untested terrestrially, imprint telltale polarimetric signatures[44;45] on magnetar spectra and pulsations that can be probed with updated telescope technology in the hard X-ray through MeV domains such as AMEGO[31].

State-of-the-Art Magnetar Models & Pertinent QED Processes

Soft X ray photon densities and magnetic field strengths are high at low altitudes, and so there the dominant energy loss mechanism for electrons is RICS, which may be regarded as cyclotron absorption followed by spontaneous re-emission, preserving the electron in the ground Landau state. In the Thomson limit, the maximum upscattered photon energy (in units of $m_e c^2$) is $\gamma_e(B/B_{\rm cr}) \sim \gamma_e^2 \epsilon_s$ while it is γ_e in the Klein-Nishina regime, for electron Lorentz factor γ_e, and surface thermal photon energy $\epsilon_s m_e c^2 \sim 0.1 - 3$ keV. The conditions for resonance are always satisfied in a thermal photon bath[39]. In high $B \gtrsim B_{\rm cr}$ fields, a full QED treatment is necessary for cyclotron lifetimes, RICS cross sections and scattering kinematics[42;46–48]. As in Thomson scattering, RICS generates distributions of photons with high *linear* polarization degree. The field direction (and electron momentum distribution) breaks spatial symmetry and acts as an optical axis. The $\perp$ (X, extraordinary) and $\|$ (O, ordinary) mode are defined as the electric field vector $\|$ or $\perp$ to the plane containing the outgoing photon $\boldsymbol{k}_f$ and magnetic field $\boldsymbol{B}_{\rm loc}$ vectors, respectively. There is an associated *energy-dependent* Doppler beaming cone for electrons in the magnetosphere; the highest energy RICS photons are sampled for electrons viewed head-on by an observer, corresponding to lines of sight that are tangent to local field lines. Therefore, different viewing angles with respect to the magnetic axis sample different electron populations and beaming geometry. The upshot is spin modulation, i.e. (polarized) pulsations, if the spin and magnetic moments are misaligned.

Strong-field Untested QED Propagation Effects: Magnetar magnetospheres are opaque to high energy photons, so that above the pair threshold around 1 MeV, pair creation strongly dominates the photon opacity. Dispersive influences of the magnetized quantum vacuum introduce birefringence, i.e. different refractive indices for the elliptical polarization eigenstates[2]; dispersion is small for $\sim$ 1 keV photons. Below pair threshold, photon splitting is the dominant attenuation mechanism in a strong magnetic field; this is a 3rd order QED process arising from vacuum polarization (virtual pairs) radiating when interacting with the field. The rate of splitting is a strong function of photon energy $\propto \epsilon^5 \mathcal{B}^6$ where $\mathcal{B}$ is the projection of the local magnetic field $\boldsymbol{B}_{\rm loc}$ onto the direction of the photon momentum. In the weakly dispersive limit, only $\perp$-mode photons may split due to kinematic selection rules[49]. However, splitting of both photon polarizations (modes) does not violate charge-parity (CP) symmetry; *it is still an open question if both modes may split in the strongly dispersive nonlinear regime of QED.* If both polarizations are permitted to split, then the *shape* of the spectral cutoff ought to follow a super-exponential shape.

Beyond QED: Axion-like particles may be produced in the hot cores of magnetars and convert into photons in the magnetosphere[50–54]. This is a strong function of core temperature, and, the unknown photon-axion coupling. To this end, line-like features in the continuum RICS background emission, unusual hard X-ray emission from hot magnetars, or unusual spectropolarimetric signatures may distinguish new physics from the exotic QED physics mentioned above in the hard X-ray or MeV domain. Thus, deep soft γ-ray observations offer the prospect of constraining such physics.

Conclusion

New, sensitive Compton and pair telescopes with polarimetric capacity such as AMEGO[31] will move our understanding of magnetars and the physics of their magnetospheres forward in a watershed fashion. Besides broadening astrophysical knowledge of magnetars, these observational capabilities will determine whether or not the exotic QED process of photon splitting in strong magnetic fields is operating in Nature. Magnetars will thus serve as a cosmic laboratory that opens windows into the physical Universe that are not presently afforded by terrestrial experiments.

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