ASTRO2020 SCIENCE WHITE PAPER

Magnetars as Astrophysical Laboratories of Extreme Quantum Electrodynamics: The Case for a Compton Telescope

Thematic Areas: ☑ Formation and Evolution of Compact Objects
☑ Cosmology and Fundamental Physics

Principal Author: Zorawar Wadiasingh
Institution: NASA Goddard Space Flight Center, Gravitational Astrophysics Laboratory
Email: zorawar.wadiasingh@nasa.gov
Phone: +1 301 286 7063

Co-authors:
George Younes, George Washington University
Matthew G. Baring, Rice University
Alice K. Harding, NASA/GSFC
Peter L. Gonthier, Hope College
Kun Hu, Rice University
Alexander van der Horst, George Washington University
Silvia Zane, University College London
Chryssa Kouveliotou, George Washington University
Andrei M. Beloborodov, Columbia University
Chanda Prescod-Weinstein, University of New Hampshire
Tanmoy Chattopadhyay, Pennsylvania State University
Sunil Chandra, North-West University Potchefstroom
Constantinos Kalapotharakos, NASA/GSFC
Kyle Parfrey, NASA/GSFC
Demos Kazanas, NASA/GSFC

Abstract: A next generation of Compton and pair telescopes that improve 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. This paper outlines the core questions pertaining to magnetars that can be addressed by such a technology. These range from global magnetar geometry and population trends, to incisive probes of hard X-ray emission locales, to providing cosmic laboratories for spectral and polarimetric testing of exotic predictions of QED, principally the prediction of the splitting of photons and magnetic pair creation. Such fundamental physics cannot yet be discerned in terrestrial experiments. State of the art modeling of the persistent hard X-ray tail emission in magnetars is presented to outline the case for powerful diagnostics using Compton polarimeters. The case highlights an inter-disciplinary opportunity to seed discovery at the interface between astronomy and physics.

1 Magnetars In a Nutshell

Neutron stars serve as useful laboratories to study physics under conditions of extreme density, gravity, and magnetic fields. Magnetars represent a topical subclass of the neutron star family. The known magnetars[1] of our galaxy possess the longest spin periods among all isolated neutron stars, yet with large spin down rates. These temporal properties imply that they are young, with an average spin down age of a few thousand years, possess the highest magnetic fields in the Universe, with polar surface values of $B_p \sim 10^{13} - 10^{15}$ G, and exhibit weak spin-down power compared to their more numerous "cousins," the canonical rotationally-powered pulsars.

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. Tellingly, their luminosities exceed their spin-down power by as much as three orders of magnitude. Accordingly, magnetars cannot be powered by spin energy loss, but instead extract their power from the immense reservoir of magnetic energy, $10^{46} - 10^{48}$ erg. They occasionally enter burst active episodes where they emit a few to hundreds of short (~ 0.1 s), bright bursts in the 5–500 keV band with $L_\gamma \sim 10^{37} - 10^{42}$ erg s^{-1}. Following the onset of such bursting activity, magnetars enter an excited X-ray state where their quiescent flux increases by factors ranging from a few to 1000 times the quiescent flux[2;3], phases named "magnetar outbursts". These phenomena are usually accompanied by strong spectral and temporal variations, e.g., hotter effective temperature, glitch and anti-glitch events, strong timing noise, and pulse profile evolution[4;5;6;7;8;9;10;11;12]. The outbursts may persist for months to years, during which the magnetar spectral and temporal properties recover to their pre-outburst behavior[2;13].

Despite the relatively low number of magnetars (23 confirmed, 6 candidates), they possess an enormous topicality, as evidenced by the shear number of dedicated reviews in the last 10 years[14;15;16;17;18;19]. Moreover, magnetars have been invoked to explain some of the extreme phenomena in the Universe, such as super-luminous supernovae[20;21], gamma-ray bursts[22;23] (GRBs), ultra-luminous X-ray sources[24;25;26;27] (ULXs), and the mysterious Fast Radio Bursts[28;29;30;31;32] (FRBs). In short, these fascinating objects remain at the forefront of astrophysics curiosity for the foreseeable future.

1.1 Current Observational Status and Gaps

The last two decades have been the golden age for nascent magnetar science. *Swift*-BAT and *Fermi*-GBM have enabled the discovery of a large number of magnetars through the detection and localization of short magnetar-like bursts[33;34], *Swift*-XRT and *RXTE*-PCA have permitted the detailed study of their temporal and spectral changes during outbursts[35;36], and last but not least *Chandra* and *XMM-Newton* have deciphered the quasi-thermal nature of their persistent soft $(0.5 - 10$ keV$)$ X-ray emission in quiescence and during outbursts.

A remarkable discovery was reported in 2004[37] of a new *persistent* spectral component in 1E 1841−045 with *RXTE* HEXTE between $10 - 150$ keV, *100% pulsed at the highest energies*. Similar detections followed for 1RXS J170849.0−400910, 4U 0142+61, and 1E 2259+586 using HEXTE and *INTEGRAL* IBIS ISGRI[38;39;40]. The higher sensitivity of *NuSTAR* enabled the detection of these hard X-ray tails in fainter magnetars; currently there are 7 magnetars that exhibit persistent hard tails during quiescence, and another 6 during outburst[3]. These hard X-ray tails exhibit spectra consistent with power laws (PL) of photon index $\Gamma \approx 1.0$, demanding drastic spectral changes at ~ 10 keV. Moreover, they dominate the energetics, 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.

Our understanding of magnetar energetics is incomplete. Given these upper limits, only a sensitive soft γ-ray observatory would ultimately uncover the peak energy of the magnetar spectral energy distributions, thereby determining their total persistent energy budget in quiescence and in outburst. Moreover, these observations would result in key observable parameters, such as the exact shape and energy of the high-energy cutoff and its variations with rotational phase. Equipped with polarization capabilities, such an observatory would also reveal the polarization degree and position angle signatures of the hard X-ray emission from magnetars. These key observables depend critically on the photon and particle interactions in one of the most extreme environments in the Universe, and may result in the first discovery of exotic quantum electrodynamic (QED) physics long thought to be operating in proximity of not only magnetars but also pulsars.

1.2 Theory in Brief

The nonthermal nature of the persistent hard X-ray tails suggests that they are powered by a relativistic electron/positron population. Current models are still in their infancy but steadily developing. 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[41;42].

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[43;44;45;46;47;48;49;50]. 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. For the magnetar context, it is crucial to recognize that fields are in the QED domain where $\hbar\omega_B \sim m_e c^2$; this defines the critical field $m_e^2 c^3/(\hbar q_e) \equiv B_{\rm cr} \approx 4.413 \times 10^{13}$ G. Rapid cyclotron cooling restricts electrons to move parallel to the field (see Fig 1). 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[50].

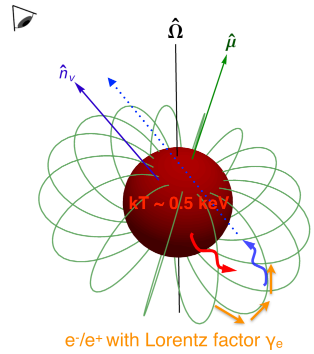

Figure 1: *In RICS, surface photons of energy $kT \sim 0.5$ keV are upscattered by relativistic electrons which follow field lines. The observer samples a small portion of the magnetosphere owing to the kinematics of RICS. For misaligned magnetic $\hat{\mu}$ and spin $\hat{\Omega}$ axes, pulsations are observed.*

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* ($\gamma + B \to e^+e^-$). These exotic QED propagation effects[51;52;53] which are as yet untested terrestrially, imprint telltale polarimetric signatures on magnetar spectra and pulsations that can be probed with updated telescope technology.

1.3 Questions That a Sensitive Compton Telescope Will Answer

Extant models of the type discussed here provide an array of possible spectral and polarization predictions that serve as a toolkit for probing both geometry and physics of magnetars. Accordingly, an array of important advances to our understanding of these topical objects can be delivered with the deployment of a mission with Compton detection technology that has both improved continuum sensitivity and polarimetric capability above 100 keV. These deliverables include

- employing variations of spectra and polarization with pulse phase to constrain the locale for hard X-ray tail emission – Doppler boosting varies substantially for different sites of scattering.
- phase-resolved spectroscopy to constrain the array of possible angles α between the rotational and magnetic axes of a magnetar. This can be determined for a variety of magnetars, and trends of α with magnetar age can be explored. Refinement of B_p estimation then becomes possible.
- fundamental QED physics can be probed by ascertaining whether photon splitting and/or pair creation impose upper limits to the emission energies. Polarimetry enhances this diagnostic.

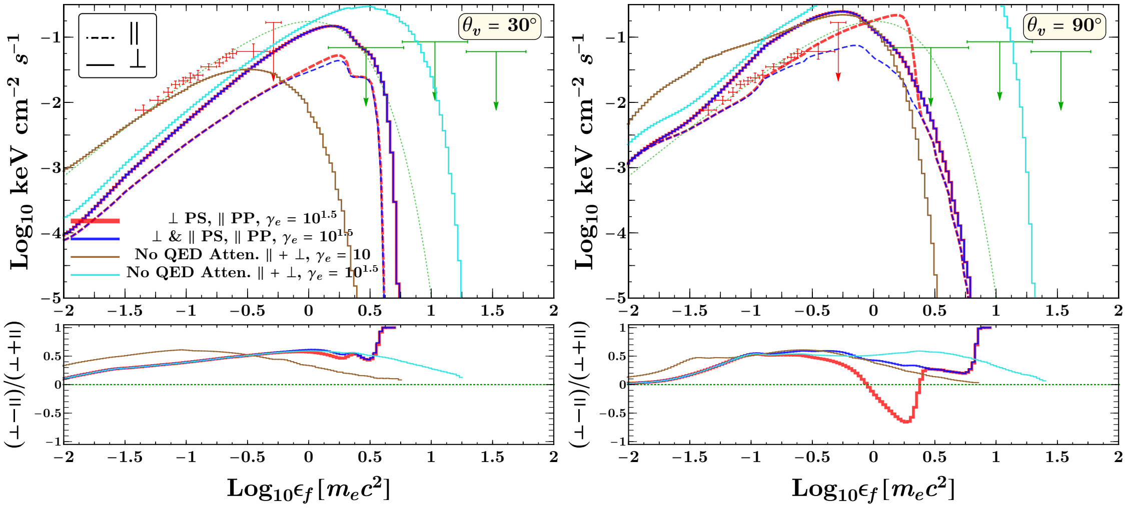

Figure 2: *Spin-phase resolved model RICS spectra of a generic magnetar (at arbitrary normalization) overlaid on phase-averaged data for 4U 0412+61 along with a PL with exponential cutoff at* 350 *keV in dotted green. The RICS emission is anticipated to be highly polarized and spin-phase dependent. The model emission is computed for surface photons of temperature* 5×10^6 *K scattered by* $\gamma_e = 10 - 10^{1.5}$ *electrons uniformly populating field bundle from magnetic footpoint colatitudes* $12 - 45°$ *for* $B_p = 10B_{\rm cr}$. **Left***: Instantaneous observer impact angle (for a particular spin phase) of* $\theta_v = 30°$ *with respect to the magnetic axis* $\hat{\mu}$*;* **Right***:* $\theta_v = 90°$. **Bottom panels***: Signed polarization degree, highlighting the spectropolarimetric signatures of resonant Compton scattering attenuated by magnetic photon splitting (PS) and/or magnetic pair production (PP).*

- exploring activation of magnetar magnetospheres following burst-active episodes relative to long-term relaxed conditions, thereby informing magnetar energetics and wind properties.

Enabling these insights advances our understanding of magnetars and their relationship to other neutron star varieties. Yet the science reach extends to GRBs, ULXs and FRBs, each with possible magnetar connections.

2 Details: 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[47]. In high $B \gtrsim B_{\rm cr}$ fields, a full QED treatment is necessary for cyclotron lifetimes, RICS cross sections and scattering kinematics[50;54;55;56]. 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 $\parallel$ (O, ordinary) mode are defined as the electric field vector $\parallel$ 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.

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[53]; dispersion is small for ~ 1 keV photons. Below pair threshold, photon splitting is the dominant attenuation mechanism in a strong magnetic field; this is a 3$^{\text{rd}}$ 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[57]. 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 non-linear regime of QED.* If both polarizations are permitted to split, then the *shape* of the spectral cutoff ought to follow a super-exponential shape.

In Fig. 2 we depict selected RICS model spectra (Wadiasingh et al., in prep). For comparison, *INTEGRAL* data and COMPTEL bounds for 4U 0142+61[39] are plotted along with a power law with exponential cutoff at 350 keV in dotted green. Hu et al. (2019, MNRAS submitted) provide a convenient parameterization of photon splitting and pair creation escape energies we use to compute photon-trajectory-dependent opacities in our code for RICS emission in Fig. 2. As is typical of scattering processes, the $\perp$ mode dominates for most energies except near the unknown cutoff – see the bottom panels. Without inclusion of QED opacities, the cutoff is kinematically attained and exponential in character; this is illustrated in the brown and cyan polarization-summed curves. In contrast, if the $\perp$ mode photon splitting and the $\parallel$ mode pair creation attenuates the spectrum, a regime of very high polarization degree is exhibited in the cutoff as depicted in the red curves. Finally, if both $\perp$ and $\parallel$ modes of splitting operate as represented by the blue curves, then a depolarization effect in the cutoff is apparent, yet with a cutoff that is no longer exponential but super-exponential. Therefore, *spectropolarimetric diagnostics of the cutoff regime of magnetars offer a powerful path to probing photon splitting*. Also, the sensitivity exhibited in Fig. 2 to θ_v indicates that phase-resolved spectropolarimetry will strongly constrain the angle α between the rotational and magnetic axes of individual magnetars (Wadiasingh et al., in prep).

3 Magnetar Soft Gamma-Ray Studies with Proposed Compton Technology

There are currently 7 magnetars that exhibit a hard X-ray tail in quiescence out of 8 observed with sensitive hard X-ray instruments such as *Suzaku* and *NuSTAR*[3]. These are depicted in Fig. 3. The energy scale covers $3 \times 10^{-3} - 40$ MeV, hence partially displays the soft X-ray quasi-thermal model (dashed-lines) and also hard power-law tails (dotted-lines). Our knowledge of these spectra extends up to $\sim 100 - 200$ keV (where it is *100% pulsed*) beyond which our observational picture is completely missing. We extrapolated the observed phase-averaged hard tails of these magnetars and adopted an 0.5 MeV exponential cutoff for all the sources. These mock soft γ-ray spectra are well below the 2σ CGRO-COMPTEL upper-limits for 4U 0142+61 and 1RXS J170849.0$-$400910 depicted in blue and yellow, respectively.

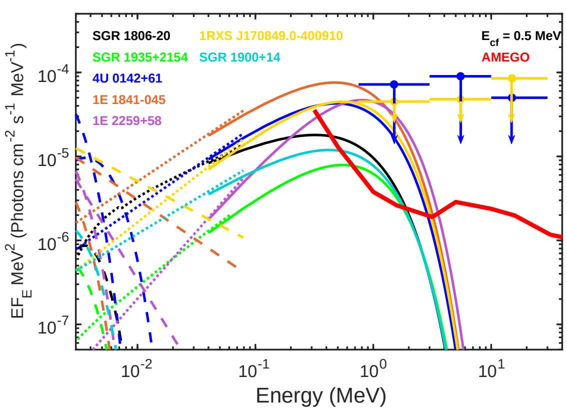

Figure 3: *Extrapolation of NuSTAR and INTEGRAL persistent phase-averaged PL spectra with a generic exponential cutoff at* 0.5 *MeV for various magnetars.*

Planned Compton telescope technology furnishes wide-field and polarization capabilities, enabling compelling time-domain and spectropolarimetric studies. The red curve of Fig. 3 denotes the 1-year sensitivity curve to the *proposed probe-class mission AMEGO*[58](similar in capabilities to its proposed European kin e-ASTROGAM[59]) and demonstrates that all seven magnetars are well

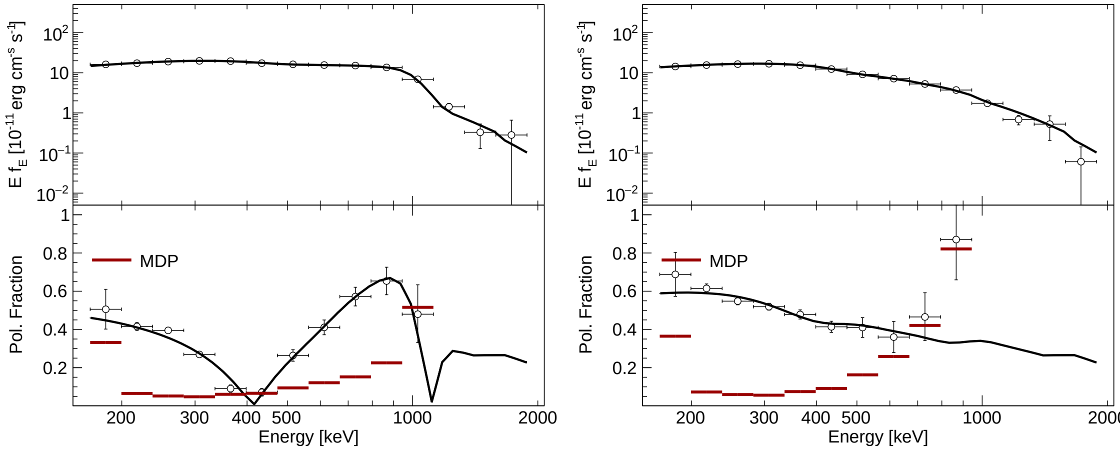

Figure 4: *Simulations of model spectra and polarization (from the right panel of Fig. 2) for 2 yrs (146 days on-time) of observations with an AMEGO-like Compton telescope for a bright magnetar. (**Left panel**) splitting of the $\perp$ (X) mode only. (**Right panel**) splitting of both $\perp$ (X) and $\|$ (O) modes. Spectropolarimetry clearly offers a path for detecting and characterizing exotic QED splitting for the first time. MDP denotes the instrumental minimum detectable polarization level.*

within the grasp of detectibility. Per our theoretical predictions, the cutoff energy may be steeper with a super-exponential shape. Similarly, simulation of a super-exponential cutoff with index of 5 and a cutoff energy of 0.75 MeV results in the detection of all seven magnetars. If some magnetar spectra extend beyond 1 MeV, an advanced pair telescope such as AdEPT[60;61] may reveal the presence of magnetic pair attenuation. Any instrument with *AMEGO*-like large FoV mission would also enable unprecedented spectral and temporal variability studies of magnetars leading up to, during, and after outbursts, a crucial element to determining the excitation locales and triggering mechanism of these active states.

We also simulated, using GPST[62], a 2-year spectrum of the $\theta_v = 90°$ models (tantamount to on-pulse phase selection) as displayed in Fig. 2 for an instrument with *AMEGO*-like spectropolarimetric capabilities (Fig. 4). We assumed a normalized flux of 2×10^{-11} erg s^{-1} cm^{-2} at 40 keV, consistent with the four brightest magnetars in Fig. 3. The left panel displays the case of photon splitting of the $\perp$ mode only, while the right panel includes both splitting modes. In either case, a detection of a high polarization degree would be a clear signature of the resonant Compton model for the emission physics. Most importantly, the cutoff shape and polarization differentiation between the two cases are unmistakable. *A detection of a polarization signature similar to the one depicted in the left panel is a "smoking-gun" evidence of photon splitting, and would be a spectacular confirmation of QED in the strong field domain.*

4 Summary

The case is presented that a new, sensitive Compton telescope with polarimetric capacity will move our understanding of magnetars and the physics of their magnetospheres forward in a watershed fashion. For the first time, the energy budget apportioned to their non-thermal signals will be measured with good precision. Pulse phase-resolved spectroscopy and polarimetry will constrain the locales possible for the origin of the hard X-ray emission. Spectropolarimetry will also enable the estimation of the inclination angle α between the magnetic and rotation axes, a key magnetar parameter. Moreover, 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. The technology that can bring about these gains for magnetars is on the near horizon, and can be applied to a multitude of other astronomical source classes with similar prospects for new and advanced insights.

This work has made use of the NASA Astrophysics Data System.

References

[1] S. A. Olausen and V. M. Kaspi, *The McGill Magnetar Catalog*, ApJS **212** (May, 2014) 6, [arXiv:1309.4167]. 1

[2] F. Coti Zelati, N. Rea, J. A. Pons, S. Campana, and P. Esposito, *Systematic study of magnetar outbursts*, MNRAS **474** (Feb., 2018) 961–1017, [arXiv:1710.04671]. 1

[3] T. Enoto, S. Shibata, T. Kitaguchi, Y. Suwa, T. Uchide, H. Nishioka, S. Kisaka, T. Nakano, H. Murakami, and K. Makishima, *Magnetar Broadband X-Ray Spectra Correlated with Magnetic Fields: Suzaku Archive of SGRs and AXPs Combined with NuSTAR, Swift, and RXTE*, ApJS **231** (July, 2017) 8, [arXiv:1704.07018]. 1, 1.1, 3

[4] P. M. Woods, V. M. Kaspi, C. Thompson, F. P. Gavriil, H. L. Marshall, D. Chakrabarty, K. Flanagan, J. Heyl, and L. Hernquist, *Changes in the X-Ray Emission from the Magnetar Candidate 1E 2259+586 during Its 2002 Outburst*, ApJ **605** (Apr., 2004) 378–399, [astro-ph/0310575]. 1

[5] G. L. Israel, S. Campana, S. Dall'Osso, M. P. Muno, J. Cummings, R. Perna, and L. Stella, *The Post-Burst Awakening of the Anomalous X-Ray Pulsar in Westerlund 1*, ApJ **664** (July, 2007) 448–457, [astro-ph/0703684]. 1

[6] R. F. Archibald, V. M. Kaspi, C.-Y. Ng, K. N. Gourgouliatos, D. Tsang, P. Scholz, A. P. Beardmore, N. Gehrels, and J. A. Kennea, *An anti-glitch in a magnetar*, Nature **497** (May, 2013) 591–593, [arXiv:1305.6894]. 1

[7] N. Rea, G. L. Israel, J. A. Pons, R. Turolla, D. Viganò, S. Zane, P. Esposito, R. Perna, A. Papitto, G. Terreran, A. Tiengo, D. Salvetti, J. M. Girart, A. Palau, A. Possenti, M. Burgay, E. Göğüş, G. A. Caliandro, C. Kouveliotou, D. Götz, R. P. Mignani, E. Ratti, and L. Stella, *The Outburst Decay of the Low Magnetic Field Magnetar SGR 0418+5729*, ApJ **770** (June, 2013) 65, [arXiv:1303.5579]. 1

[8] V. M. Kaspi, R. F. Archibald, V. Bhalerao, F. Dufour, E. V. Gotthelf, H. An, M. Bachetti, A. M. Beloborodov, S. E. Boggs, F. E. Christensen, W. W. Craig, B. W. Grefenstette, C. J. Hailey, F. A. Harrison, J. A. Kennea, C. Kouveliotou, K. K. Madsen, K. Mori, C. B. Markwardt, D. Stern, J. K. Vogel, and W. W. Zhang, *Timing and Flux Evolution of the Galactic Center Magnetar SGR J1745-2900*, ApJ **786** (May, 2014) 84, [arXiv:1403.5344]. 1

[9] F. Coti Zelati, N. Rea, A. Papitto, D. Viganò, J. A. Pons, R. Turolla, P. Esposito, D. Haggard, F. K. Baganoff, G. Ponti, G. L. Israel, S. Campana, D. F. Torres, A. Tiengo, S. Mereghetti, R. Perna, S. Zane, R. P. Mignani, A. Possenti, and L. Stella, *The X-ray outburst of the Galactic Centre magnetar SGR J1745-2900 during the first 1.5 year*, MNRAS **449** (May, 2015) 2685–2699, [arXiv:1503.01307]. 1

[10] P. Scholz, V. M. Kaspi, and A. Cumming, *The Long-term Post-outburst Spin Down and Flux Relaxation of Magnetar Swift J1822.3-1606*, ApJ **786** (May, 2014) 62, [arXiv:1401.6965]. 1

[11] J. A. J. Alford and J. P. Halpern, *Evolution of the X-Ray Properties of the Transient Magnetar XTE J1810-197*, ApJ **818** (Feb., 2016) 122, [arXiv:1601.00757]. 1

[12] G. Younes, C. Kouveliotou, A. Jaodand, M. G. Baring, A. J. van der Horst, A. K. Harding, J. W. T. Hessels, N. Gehrels, R. Gill, D. Huppenkothen, J. Granot, E. Göğüş, and L. Lin, *X-Ray and Radio Observations of the Magnetar SGR J1935+2154 during Its 2014, 2015, and 2016 Outbursts*, ApJ **847** (Oct., 2017) 85, [arXiv:1702.04370]. 1

[13] G. Younes, M. G. Baring, C. Kouveliotou, A. Harding, S. Donovan, E. Göğüş, V. Kaspi, and J. Granot, *The Sleeping Monster: NuSTAR Observations of SGR 1806-20, 11 Years After the Giant Flare*, ApJ **851** (Dec., 2017) 17, [arXiv:1711.00034]. 1

[14] S. Mereghetti, *The strongest cosmic magnets: soft gamma-ray repeaters and anomalous X-ray pulsars*, A&A Rev **15** (July, 2008) 225–287, [arXiv:0804.0250]. 1

[15] N. Rea and P. Esposito, *Magnetar outbursts: an observational review*, in High-Energy Emission from Pulsars and their Systems (D. F. Torres and N. Rea, eds.), p. 247, 2011. arXiv:1101.4472. 1

[16] R. Turolla, S. Zane, and A. L. Watts, *Magnetars: the physics behind observations. A review*, Reports on Progress in Physics **78** (Nov., 2015) 116901, [arXiv:1507.02924]. 1

[17] S. Mereghetti, J. A. Pons, and A. Melatos, *Magnetars: Properties, Origin and Evolution*, Space Science Rev. **191** (Oct., 2015) 315–338, [arXiv:1503.06313]. 1

[18] V. M. Kaspi and A. M. Beloborodov, *Magnetars*, Ann. Rev. Astron. Astrophys. **55** (Aug., 2017) 261–301, [arXiv:1703.00068]. 1

[19] P. Esposito, N. Rea, and G. L. Israel, *Magnetars: a short review and some sparse considerations*, arXiv e-prints (Mar, 2018) arXiv:1803.05716, [arXiv:1803.05716]. 1

[20] D. Kasen and L. Bildsten, *Supernova Light Curves Powered by Young Magnetars*, ApJ **717** (July, 2010) 245–249, [arXiv:0911.0680]. 1

[21] C. Inserra, S. J. Smartt, A. Jerkstrand, S. Valenti, M. Fraser, D. Wright, K. Smith, T.-W. Chen, R. Kotak, A. Pastorello, M. Nicholl, F. Bresolin, R. P. Kudritzki, S. Benetti, M. T. Botticella, W. S. Burgett, K. C. Chambers, M. Ergon, H. Flewelling, J. P. U. Fynbo, S. Geier, K. W. Hodapp, D. A. Howell, M. Huber, N. Kaiser, G. Leloudas, L. Magill, E. A. Magnier, M. G. McCrum, N. Metcalfe, P. A. Price, A. Rest, J. Sollerman, W. Sweeney, F. Taddia, S. Taubenberger, J. L. Tonry, R. J. Wainscoat, C. Waters, and D. Young, *Super-luminous Type Ic Supernovae: Catching a Magnetar by the Tail*, ApJ **770** (June, 2013) 128, [arXiv:1304.3320]. 1

[22] J. C. Wheeler, I. Yi, P. Höflich, and L. Wang, *Asymmetric Supernovae, Pulsars, Magnetars, and Gamma-Ray Bursts*, ApJ **537** (July, 2000) 810–823, [astro-ph/9909293]. 1

[23] A. Rowlinson, P. T. O'Brien, B. D. Metzger, N. R. Tanvir, and A. J. Levan, *Signatures of magnetar central engines in short GRB light curves*, MNRAS **430** (Apr., 2013) 1061–1087, [arXiv:1301.0629]. 1

[24] M. Bachetti, F. A. Harrison, D. J. Walton, B. W. Grefenstette, D. Chakrabarty, F. Fürst, D. Barret, A. Beloborodov, S. E. Boggs, F. E. Christensen, W. W. Craig, A. C. Fabian, C. J. Hailey, A. Hornschemeier, V. Kaspi, S. R. Kulkarni, T. Maccarone, J. M. Miller, V. Rana, D. Stern, S. P. Tendulkar, J. Tomsick, N. A. Webb, and W. W. Zhang, *An ultraluminous X-ray source powered by an accreting neutron star*, Nature **514** (Oct., 2014) 202–204, [arXiv:1410.3590]. 1

[25] G. L. Israel, A. Belfiore, L. Stella, P. Esposito, P. Casella, A. De Luca, M. Marelli, A. Papitto, M. Perri, S. Puccetti, G. A. R. Castillo, D. Salvetti, A. Tiengo, L. Zampieri, D. D'Agostino, J. Greiner, F. Haberl, G. Novara, R. Salvaterra, R. Turolla, M. Watson, J. Wilms, and A. Wolter, *An accreting pulsar with extreme properties drives an ultraluminous x-ray source in NGC 5907*, Science **355** (Feb., 2017) 817–819, [arXiv:1609.07375]. 1

[26] K. Y. Ekşi, İ. C. Andaç, S. Çıkıntoğlu, A. A. Gençali, C. Güngör, and F. Öztekin, *The ultraluminous X-ray source NuSTAR J095551+6940.8: a magnetar in a high-mass X-ray binary*, MNRAS **448** (Mar., 2015) L40–L42, [arXiv:1410.5205]. 1

[27] S. Dall'Osso, R. Perna, and L. Stella, *NuSTAR J095551+6940.8: a highly magnetized neutron star with super-Eddington mass accretion*, MNRAS **449** (May, 2015) 2144–2150, [arXiv:1412.1823]. 1

[28] Y. Lyubarsky, *A model for fast extragalactic radio bursts*, MNRAS **442** (July, 2014) L9–L13, [arXiv:1401.6674]. 1

[29] K. Masui, H.-H. Lin, J. Sievers, C. J. Anderson, T.-C. Chang, X. Chen, A. Ganguly, M. Jarvis, C.-Y. Kuo, Y.-C. Li, Y.-W. Liao, M. McLaughlin, U.-L. Pen, J. B. Peterson, A. Roman, P. T. Timbie, T. Voytek, and J. K. Yadav, *Dense magnetized plasma associated with a fast radio burst*, Nature **528** (Dec., 2015) 523–525, [arXiv:1512.00529]. 1

[30] J. I. Katz, *How Soft Gamma Repeaters Might Make Fast Radio Bursts*, ApJ **826** (Aug., 2016) 226, [arXiv:1512.04503]. 1

[31] B. D. Metzger, E. Berger, and B. Margalit, *Millisecond Magnetar Birth Connects FRB 121102 to Superluminous Supernovae and Long-duration Gamma-Ray Bursts*, ApJ **841** (May, 2017) 14, [arXiv:1701.02370]. 1

[32] A. M. Beloborodov, *A Flaring Magnetar in FRB 121102?*, ApJL **843** (July, 2017) L26, [arXiv:1702.08644]. 1

[33] A. J. van der Horst, V. Connaughton, C. Kouveliotou, E. Göğüş, Y. Kaneko, S. Wachter, M. S. Briggs, J. Granot, E. Ramirez-Ruiz, P. M. Woods, R. L. Aptekar, S. D. Barthelmy, J. R. Cummings, M. H. Finger, D. D. Frederiks, N. Gehrels, C. R. Gelino, D. M. Gelino, S. Golenetskii, K. Hurley, H. A. Krimm, E. P. Mazets, J. E. McEnery, C. A. Meegan, P. P. Oleynik, D. M. Palmer, V. D. Pal'shin, A. Pe'er, D. Svinkin, M. V. Ulanov, M. van der Klis, A. von Kienlin, A. L. Watts, and C. A. Wilson-Hodge, *Discovery of a New Soft Gamma Repeater: SGR J0418 + 5729*, ApJL **711** (Mar., 2010) L1–L6, [arXiv:0911.5544]. 1.1

[34] J. A. Kennea, D. N. Burrows, C. Kouveliotou, D. M. Palmer, E. Göğüş, Y. Kaneko, P. A. Evans, N. Degenaar, M. T. Reynolds, J. M. Miller, R. Wijnands, K. Mori, and N. Gehrels, *Swift Discovery of a New Soft Gamma Repeater, SGR J1745-29, near Sagittarius A**, ApJL **770** (June, 2013) L24, [arXiv:1305.2128]. 1.1

[35] P. M. Woods, C. Kouveliotou, M. H. Finger, E. Göğüş, C. A. Wilson, S. K. Patel, K. Hurley, and J. H. Swank, *The Prelude to and Aftermath of the Giant Flare of 2004 December 27: Persistent and Pulsed X-Ray Properties of SGR 1806-20 from 1993 to 2005*, ApJ **654** (Jan., 2007) 470–486, [astro-ph/0602402]. 1.1

[36] F. Coti Zelati, N. Rea, J. A. Pons, S. Campana, and P. Esposito, *Systematic study of magnetar outbursts*, MNRAS **474** (Feb., 2018) 961–1017, [arXiv:1710.04671]. 1.1

[37] L. Kuiper, W. Hermsen, and M. Mendez, *Discovery of Hard Nonthermal Pulsed X-Ray Emission from the Anomalous X-Ray Pulsar 1E 1841-045*, ApJ **613** (Oct., 2004) 1173–1178, [astro-ph/0404582]. 1.1

[38] L. Kuiper, W. Hermsen, P. R. den Hartog, and W. Collmar, *Discovery of Luminous Pulsed Hard X-Ray Emission from Anomalous X-Ray Pulsars 1RXS J1708-4009, 4U 0142+61, and 1E 2259+586 by INTEGRAL and RXTE*, ApJ **645** (July, 2006) 556–575, [astro-ph/0603467]. 1.1

[39] P. R. den Hartog, L. Kuiper, W. Hermsen, V. M. Kaspi, R. Dib, J. Knödlseder, and F. P. Gavriil, *Detailed high-energy characteristics of AXP 4U 0142+61. Multi-year observations with INTEGRAL, RXTE, XMM-Newton, and ASCA*, A&A **489** (Oct., 2008) 245–261, [arXiv:0804.1640]. 1.1, 2

[40] P. R. den Hartog, L. Kuiper, and W. Hermsen, *Detailed high-energy characteristics of AXP 1RXS J170849-400910. Probing the magnetosphere using INTEGRAL, RXTE, and XMM-Newton*, A&A **489** (Oct., 2008) 263–279, [arXiv:0804.1641]. 1.1

[41] A. M. Beloborodov and C. Thompson, *Corona of Magnetars*, ApJ **657** (Mar., 2007) 967–993, [astro-ph/0602417]. 1.2

[42] A. M. Beloborodov, *Electron-Positron Flows around Magnetars*, ApJ **777** (Nov., 2013) 114, [arXiv:1209.4063]. 1.2

[43] M. G. Baring and A. K. Harding, *Resonant Compton upscattering in anomalous X-ray pulsars*, Astr. Space Sci. **308** (Apr., 2007) 109–118, [astro-ph/0610382]. 1.2

[44] R. Fernández and C. Thompson, *Resonant Cyclotron Scattering in Three Dimensions and the Quiescent Nonthermal X-ray Emission of Magnetars*, ApJ **660** (May, 2007) 615–640, [astro-ph/0608281]. 1.2

[45] L. Nobili, R. Turolla, and S. Zane, *X-ray spectra from magnetar candidates - II. Resonant cross-sections for electron-photon scattering in the relativistic regime*, MNRAS **389** (Sept., 2008) 989–1000, [arXiv:0806.3714]. 1.2

[46] S. Zane, R. Turolla, L. Nobili, and N. Rea, *Modeling the broadband persistent emission of magnetars*, Advances in Space Research **47** (Apr., 2011) 1298–1304, [arXiv:1008.1537]. 1.2

[47] M. G. Baring, Z. Wadiasingh, and P. L. Gonthier, *Cooling Rates for Relativistic Electrons Undergoing Compton Scattering in Strong Magnetic Fields*, ApJ **733** (May, 2011) 61, [arXiv:1103.3356]. 1.2, 2

[48] A. M. Beloborodov, *On the Mechanism of Hard X-Ray Emission from Magnetars*, ApJ **762** (Jan., 2013) 13, [arXiv:1201.0664]. 1.2

[49] R. Hascoët, A. M. Beloborodov, and P. R. den Hartog, *Phase-resolved X-Ray Spectra of Magnetars and the Coronal Outflow Model*, ApJL **786** (May, 2014) L1, [arXiv:1401.3406]. 1.2

[50] Z. Wadiasingh, M. G. Baring, P. L. Gonthier, and A. K. Harding, *Resonant Inverse Compton Scattering Spectra from Highly Magnetized Neutron Stars*, ApJ **854** (Feb., 2018) 98, [arXiv:1712.09643]. 1.2, 2

[51] A. K. Harding, M. G. Baring, and P. L. Gonthier, *Photon-Splitting Cascades in Gamma-Ray Pulsars and the Spectrum of PSR 1509-58*, ApJ **476** (Feb., 1997) 246–260, [astro-ph/9609167]. 1.2

[52] M. G. Baring and A. K. Harding, *Photon Splitting and Pair Creation in Highly Magnetized Pulsars*, ApJ **547** (Feb., 2001) 929–948, [astro-ph/0010400]. 1.2

[53] A. K. Harding and D. Lai, *Physics of strongly magnetized neutron stars*, Reports on Progress in Physics **69** (Sept., 2006) 2631–2708, [astro-ph/0606674]. 1.2, 2

[54] P. L. Gonthier, A. K. Harding, M. G. Baring, R. M. Costello, and C. L. Mercer, *Compton Scattering in Ultrastrong Magnetic Fields: Numerical and Analytical Behavior in the Relativistic Regime*, ApJ **540** (Sept., 2000) 907–922, [astro-ph/0005072]. 2

[55] M. G. Baring, P. L. Gonthier, and A. K. Harding, *Spin-dependent Cyclotron Decay Rates in Strong Magnetic Fields*, ApJ **630** (Sept., 2005) 430–440, [astro-ph/0505327]. 2

[56] P. L. Gonthier, M. G. Baring, M. T. Eiles, Z. Wadiasingh, C. A. Taylor, and C. J. Fitch, *Compton scattering in strong magnetic fields: Spin-dependent influences at the cyclotron resonance*, Phys. Rev. D **90** (Aug., 2014) 043014, [arXiv:1408.2146]. 2

[57] S. L. Adler, *Photon splitting and photon dispersion in a strong magnetic field.*, Annals of Physics **67** (1971) 599–647. 2

[58] AMEGO, *All Sky Medium Gamma-Ray Observatory*, https://asd.gsfc.nasa.gov/amego/index.html (2019). 3

[59] A. de Angelis, V. Tatischeff, I. A. Grenier, J. McEnery, M. Mallamaci, M. Tavani, U. Oberlack, L. Hanlon, R. Walter, A. Argan, and et al., *Science with e-ASTROGAM. A space mission for MeV-GeV gamma-ray astrophysics*, Journal of High Energy Astrophysics **19** (Aug., 2018) 1–106, [arXiv:1711.01265]. 3

[60] S. D. Hunter, P. F. Bloser, G. O. Depaola, M. P. Dion, G. A. DeNolfo, A. Hanu, M. Iparraguirre, J. Legere, F. Longo, M. L. McConnell, S. F. Nowicki, J. M. Ryan, S. Son, and F. W. Stecker, *A pair production telescope for medium-energy gamma-ray polarimetry*, Astroparticle Physics **59** (Jul, 2014) 18–28, [arXiv:1311.2059]. 3

[61] S. D. Hunter, *The advanced energetic pair telescope for gamma-ray polarimetry*, in Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, vol. 10699 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, p. 106992M, July, 2018. 3

[62] GPST, *The Gamma-ray Polarimetry Simulation Toolkit*, https://github.com/ComPair/GPST (2019). 3