Magnetars and Fast Radio Bursts

Christopher Thompson, CITA, University of Toronto

Bright, narrow radio bursts have been detected from a Galactic magnetar in outburst, but only limited progress has been made connecting this radio emission with the mechanism producing the much more luminous X-ray bursts. This talk will describe a simple mechanism relating the emission of 10-100 cm waves to a dynamic magnetic field that develops small-scale current structure. (Many more details can be found in the preprint arXiv:2209.11136.) Strong independent evidence for such structure during a magnetar outburst comes from the observation of quasi-thermal X-radiation. (High-wavenumber current perturbations mediate energy transfer between the magnetic field and embedded electrons and positrons.)

On occasion, the perturbed magnetic field may be ejected, forming a relativistically expanding pulse hundreds of kilometers wide. The small scale modes become frozen by the expansion; the focus is on their linear interaction with large-scale shocks. This couples the subluminal modes to a superluminal wave which can escape and be detected as a radio wave. In particular, a solution is found to linear perturbations of a relativistically magnetized shock wave. This generalizes the problem of an acoustic wave interacting with a shock to the richer array of modes present in magnetized plasma. Zero-frequency plasma modes colliding with the shock excite dynamic electromagnetic oscillations on the downstream side. This secondary emission is dominated by the ordinary wave – orthogonal in polarization to that produced by the shock maser instability. The amplitude of the reflected wave is negligible.

This mechanism has substantial advantages over the two main alternatives (the maser and reconnection-induced X-mode emission). First, in contrast with the maser, the process is efficient even if the upstream particles are relativistically warm and the shock is of moderate strength. Second, the formation of a turbulent spectrum of modes guarantees the presence of waves of size less than 10^{-6} of the outflow width but carrying $10^{-4} - 10^{-3}$ of the energy flux. Relativistic expansion stores energy in modes of wavelength in the radio range by limiting the cascade energy flux into particles.

My other recent work on magnetars and radio pulsars has been concerned with poorly understood physical processes, such as: How is a global yielding event with a duration of 0.1 seconds or longer triggered in a magnetar? The interactions of photons, electrons and positrons are radically altered in a super-QED magnetic field; how is a strong electric current and electromagnetic pulse excited and supported outside the star? What are the dominant instabilities to which this current is susceptible, and how is energy transferred from the magnetic field to charged particles and to radio waves? (See Thompson 2008, ApJ; Thompson, Yang and Ortiz 2017, ApJ; Kostenko and Thompson 2018, 2019, ApJ; Thompson and Kostenko 2020, ApJ; Thompson 2022a,b, ApJ.)

Other work connected with fast radio bursts has focused on the interconnection between gravitational lensing and plasma interaction of radio waves, exploring the radical (?) possibility that repeating fast radio bursts are emitted close to the event horizons of weakly accreting intermediate-mass black holes. A 2017 paper solved the problem of the 'Fast Radio Burst Green Function'. It was shown how a thin and subluminally expanding relativistic shell can linearly transform to a superluminal mode, and how the shell can 'upscatter' spatial structure in an ambient magnetic field into frequency structure in the bounced electromagnetic wave.

Yet earlier work investigated the origin of extreme magnetism in convecting and accreting proto-neutron stars. With R. Duncan, extreme magnetism in the remnant neutron star was connected with the phenomenon of repeating soft gamma-ray bursts and with a class of thermally emitting pulsating X-ray sources in the Milky Way. I also identified ultraluminous rotationally driven magnetized outflows as the source of the broader gamma-ray burst phenomenon, found a self-regulating mechanism localizing the dissipation in these outflows, with M. Russo explained how they accelerate, and with R. Gill worked out a constrained theory of gamma-ray emission based on simple properties of strongly magnetized pair plasmas. Novel aspects of QED processes operating in ultrastrong magnetic fields have been analyzed, mainly with A. Kostenko (photon splitting/merging, annihilation bremsstrahlung, etc) which explain key aspects of the X-ray spectra of bursting and quiescent magnetars. The decay of the magnetic field is driven by processes operating both inside and outside the star. With Kostenko I developed a simple solution to the external circuit and with Duncan, H. Yang and others have worked out the effects of temperature feedback on magnetic transport in the stellar interior, as well as a self-consistent global mode of yielding. Other related publications have focused on angular momentum transport and magnetic field growth in evolving stars.