Circular polarization and Faraday rotation

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The radio emission from extragalactic radio sources is due to synchrotron emission which is partially linearly polarized. As radio waves propagate through the interstellar medium (ISM), the small difference in refractive index between left and right hand polarized waves causes the plane of linear polarization to rotate. The sign of this Faraday rotation depends on the sign of the projection, B_z, of the local magnetic field in the ISM on the ray path.

Extragalactic sources typically also have a small degree of circular polarization, whose origin is uncertain. One model attributes the circular polarization to a propagation effect in the ISM, arising from the regions where B_z reverses sign

The project will involve integrating a matrix equation (for the Stokes parameters) along the ray path through an idealized model for the region where B_z changes sign. The predictions of the model will be compare with observational data.

Melrose, D. B. & McPhedran, R. C. *Electromagnetic processes in dispersive media*. Cambridge University Press, 1991, p. 189

Melrose, D. B. 2010, "Faraday rotation: Effect of magnetic field reversals", Astrophys. J. 725, 1600

Kepler superflares

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Data from NASA's Kepler mission is used mostly to search for exo-planets and for asteroseismology, but it also allows identification of stellar flares, which cause transient brightness increases in the light from individual stars (Maehara et al. 2012). These events are the counterparts of solar flares – magnetic explosions in the Sun's atmosphere – on a larger scale. Stellar flares may be 10^5 times as energetic as the largest solar flares, but they follow a similar power-law size distribution to solar flares (Shibata et al. 2013), and are also magnetic in nature. Kepler has observed light curves for a large number of stars since its launch in 2009, providing excellent statistics on stellar superflares. This project will investigate the similarities and differences between the statistics of stellar superflares and solar flares. The statistical properties of events from individual solar-like stars will be examined, and waiting-time distributions constructed for time series of these events. The results will be related back to the physical mechanisms believed to underlie stellar and solar flares. The project has scope for data analysis, theory and modeling.

Maehara H. et al. 2012, "Superflares on solar-type stars", Nature 485, 478, doi:10.1038/nature11063

Shibata, K. et al. 2013, Publ. Astron. Soc. Jpn. 65, 49

Magnetar radiation belts

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Magnetars are a class of pulsar-like neutron stars with exceptionally strong magnetic fields and slow rotation rates. The are observed primarily from their high-energy emission, in both Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs). Outbursts on SGRs are the most powerful known examples of magnetic explosions. A subset of magnetars are also observed as radio pulsars.

A favored model for the hard X-ray emission from magnetars involves high-energy pairs trapped in closed magnetic field lines (Beloborodov 2013). Such trapping is analogous to energetic particles trapped in the Earth's radiation belts, also known as the Van Allen belts (Luo & Melrose 2008). There is an extensive literature on how trapped particles are lost through precipitation into the Earth's atmosphere.

This project will involve adapting models for the loss of trapped particles from the Earth's radiation belts to trapped relativistic particles in a magnetar magnetosphere. A specific question that will be addressed is: Do the trapped electrons and positrons precipitate, like the terrestrial analog, or do they slow down and annihilate in the magnetosphere? Observational implications of both possibilities will be explored.

Beloborodov, A.M., 2013, "On the mechanism of hard X-ray emission from magnetars" Astrophys. J. 762, 13

Luo, Q., Melrose, D.B., 2008, "Pulsar transient radio emission", in Y.-F. Yuan, X.-D. Li, D. Lai (eds) *Astrophysics of Compact Objects*, AIP Conference Proceedings 968, p. 159

Magnetic null points and electrical current systems in the solar corona

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Large scale electrical current systems flowing in the ionised solar corona above sunspots provide the energy for solar flares. Because of the high electrical conductivity of the corona, the magnetic field is "frozen in" to the plasma and cannot change its connectivity, except during the energy release process (magnetic reconnection) casuing flares. The connectivity of the field in the corona is defined by separatrix surfaces between sets of field lines with different connectivity. These surfaces intersect in special lines (separatrices) which begin and end on null points, where the field is zero. The theory developed to describe the field topology has largely ignored the role of electric currents. The coronal field is "force-free" due to the strong magnetic field and the low plasma density, meaning that currents are everywhere parallel to field lines. However, the currents may vary in magnitude and sign between different field lines.

This project will investigate the structure of electrical current systems and their relation to the field topology, in particular the appearance and location of magnetic nulls, using a nonlinear force-free code applied to simple quadrupolar-field boundary conditions. The project will involve a mix of theory, computation, as well as scientific visualisation of three-dimensional vector fields. The numerical work will require use of an existing code, as well as writing new codes to investigate field and current structures.

Rotational perversity: the rattleback

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The rattleback is a physics toy with a preferred sense of rotation. It is a small object in the shape of a boat hull but with an asymmetrical cross section. When it is spun horizontally on a surface in its non-preferred direction, the rattleback starts rocking and slows down, and then starts spinning in its preferred direction. The friction force at the point of contact with the surface produces a torque which leads to the change in rotation, but the explanation is quite involved. Past studies include analytic theoretical models (Bondi 1986; Franti 2013), and numerical solution of the equations of motion (Garcia & Hubbard 1988). Recently Cross (2013) investigated rattlebacks and filmed their motion[1], and presented an intuitive explanation. In this project the motion of the rattleback will be investigated

[1] For high-speed movies of rattlebacks in action, see the Spinning Tops link on Rod Cross's homepage: `http://www.physics.usyd.edu.au/~cross`.

using the published models, and by numerical solution of the equations of motion. The explanation given by Cross (2013) will be compared with the results of computation, as well as the analytic models. The project has scope for theory, computation, and data analysis (comparison of the models and the rattleback's observed motion).

Bondi, H. 1986, "The rigid body dynamics of unidirectional spin", Proc. Royal Soc. Lond. Ser. A 405, 265
Cross, R. C. 2013, "Rocking and rolling rattlebacks", submitted to The Physics Teacher
Franti, L. 2013, "On the rotational dynamics of the rattleback", Cent. Eur. J. Phys. 11, 162
Garcia, A. & Hubbard, M. 1988, "Spin reversal of the rattleback: Theory and Experiment", Proc. Royal Soc. Lond. Ser. A 418, 165

Solar flares: energetic and electron acceleration

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Solar flares are explosive events in the solar corona in which stored magnetic energy is converted into kinetic energy in mass motions and into energetic particles. In some ("compact") flares most of the energy goes into a huge number of electrons with a typical energy of 10^4 eV.

There is no consensus on the electrodynamics processes involved in flares. One problem concerns the global energetics. For example, to explain a flare in which the power released is of order $P = 10^{21}$ W in terms of $P = I\Phi$, where $I = 10^{11}$–10^{12} A is of order the current known to flow in flaring loops, requires a potential $V = 10^9$–10^{10} V, for which there is no direct evidence. The energy of the electrons suggests $V \approx 10^4$ V, which is smaller by a factor $\approx 10^6$. Another problem is that the number of energetic electrons accelerated greatly exceeds (by a similar factor $\approx 10^6$) the number stored in the flaring region prior to the flare. One recent suggestion for overcoming these difficulties involves a return current, $\approx 10^6$ times the net current, that resupplies the electrons, and can account for the power with $\Phi \approx 10^4$ V.

This project will involve developing detailed models that involve the return current and the electron acceleration, and comparing the predictions of these models with observational data on solar flares.

For cartoon descriptions of solar flares see H. S. Hudson's "Grand Archive of Flare and CME Cartoons" http://solarmuri.ssl.berkeley.edu/ hhudson/cartoons/
Melrose, D. B. 2012, "Generic model for magnetic explosions applied to solar flares", Astrophys. J. 749, 58
Melrose, D. B. 2012, "Magnetic explosions: Role of the inductive electric field", Astrophys. J. 749, 59

Spin-dependent plasma response

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The response of a plasma may be described by its dielectric tensor, which determines the properties of waves in the plasma, and various other electrodynamic properties of the plasma. The response depends on the electron spin, when the electrons have a net average spin, as in a paramagnetic or ferromagnetic medium for example.

A quasi-classical model for the spin has been used widely in recent years to develop models for spin dependent effects. In such models, the spin is described as a classical vector that precesses in the magnetic field. However, a recent exact calculation using relativistic quantum mechanics does not reproduce the semi-classical results in a consistent way.

This project will involve applying the exact theory to some simple models that can be compared with the quasi-classical models. The objectives will be to identify why the quasi-classical and exact theories do not agree, and to determine when (if ever) the use of quasi-classical models can be justified.

Understanding the spinning egg

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If a hard-boiled egg is placed onto a horizontal surface and spun rapidly about a vertical axis, with the long axis of the egg initially horizontal, then the egg tends to rise, such that the long axis of the egg becomes vertical. If the egg is spun rapidly enough it can rise to a "sleeping position" with the rotation axis vertical. If spun more slowly, it rises to an intermediate position, and precesses about the vertical axis without further rise. The rise must be due to the torque imparted by the friction force at the point of contact of the egg with the surface, but the explanation is not straightforward: the frictional torque due to the initial spin of the egg exerts a torque in the wrong direction to produce the observed rise. An explanation has been given in terms of an "adiabatic invariant" derived from the (Euler) equations of motion (Moffat, Shimomura & Branicki 2004), but this explanation lacks a correspondingly simple physical interpretation, and numerical solution of the equations indicates that the quantity is only very approximately conserved (Cross 2013). Recently, an experimental investigation was conducted by Cross (2013), resulting in a more physically intuitive explanation for the rise of the egg in terms of the "gyroscopic resistance" force. In this project the dynamics of the egg will be revisited, in an effort to better understand the dynamics, and in particular to further investigate the adiabatic invariant, or "Jellet constant". The project will involve theory, computation, and possibly comparison with observations.

Moffatt, H.K., Shimomura, Y., & Branicki, M. 2004, Dynamics of an asymmetric body spinning on a horizontal surface. I. Stability and the gyroscopic approximation", Proc. R. Soc. Lond. A 460, 3643-3672

Cross, R.C. 2013, "Why does a spinning egg rise?", submitted to the American Journal of Physics