in a direction that counteracts any local anisotropy. In most cases, and for a broad band of whistler-mode frequencies, this usually induces the electrons to diffuse into small-pitch-angle trajectories (in a direction almost parallel to the magnetic field), to lose energy (which in turn amplifies the waves), and to eventually precipitate into the Earth's upper atmosphere. But for some of the electrons injected into the magnetosphere at larger pitch angles, such resonant effects can have the opposite effect, causing them to gain ever more energy, until they reach relativistic speeds and become trapped in the geomagnetic field. Gyro-resonant wave acceleration is favoured in regions of low particle density where the phase velocity of the waves becomes large. The peaks in phase-space density that Chen *et al.* observe are near 5.5 Re, and generally lie outside the region of high-density cold plasma, as required for efficient acceleration.

The latest observations[7] indicate that we should adopt a new paradigm for producing the outer radiation belt, as suggested in Fig. 1. Wave acceleration requires a seed population of keV electrons to excite the waves, but there is plentiful evidence that this can be supplied from the outer regions by induced electric fields as a result of the substorm cycle — a cycle of energy storage in the magnetic field followed by explosive conversion into particle energy by magnetic reconnection. Radial diffusion may also help to supply the lower-energy seed population. As low-energy electrons penetrate closer to the Earth they develop an anisotropic distribution which becomes unstable, excites electromagnetic waves, and accelerates electrons via gyro-resonant interactions. This process should form a peak in the accelerated electron distribution followed by radial diffusion to fill up the entire outer radiation belt. Moreover, as all the outer magnetized planets have electron radiation belts and all have been observed to support whistler mode waves, acceleration by gyro-resonant wave–particle interactions may be more common throughout the Solar system than was first suspected.

Although the present results may provide a resolution to the debate over which mechanism is the dominant cause of relativistic electron acceleration, there are still many questions to answer. The radiation belts are intensified in only 53% of geomagnetic storms and most likely to occur during periods of fast solar wind speeds exceeding 500 km s^{-1} — why this could be is unclear. The role of whistler waves is certainly likely to be important, but the exact role in electron acceleration and loss by many other types of waves, and how the solar wind provides the source of free energy to drive the waves, remains to be explored. And beyond such fundamental issues lies the wider implications that these processes could have, such as for precipitation on atmospheric chemistry and ozone depletion. New satellite missions are needed to understand these issues.

Interest in the radiation belts is far from just academic. Relativistic electrons — known as 'killer electrons' — cause radiation damage to satellites, resulting in malfunctions and shortening their operational lives. During the 2003 Hallowe'en storm, which caused the radiation belts to drain and reform closer to the Earth, more than 30 satellites reported malfunctions, and one was a total loss. A modern telecommunications satellite costs about US$250 million to build, $100 million to launch into geostationary orbit, and annual insurance premiums are typically between 3 and 5% of the sum insured. With more than 300 satellites in geosynchronous orbit, and a growing reliance on satellite technology, this represents a huge investment in need of protection. Understanding radiation belt dynamics should help us to better manage this risk.

References

1. Schulz, M. & Lanzerotti L. *Particle Diffusion in the Radiation Belts* (Springer, New York, 1974).
2. Elkington, S. R., Hudson, M. K. & Chan, A. A. *Geophys. Res. Lett.* **26,** 3273–3276 (1999).
3. Horne, R. B. & Thorne, R. M. *Geophys. Res. Lett.* **25,** 3011–3014 (1998).
4. Summers, D., Thorne, R. M. & Xiao, F. L. *Geophys. Res. Lett.* **103,** 20487–20500 (1998).
5. Horne, R. B. *et al. Nature*, **437,** 227–230 (2005).
6. Loto'aniu, T. M. *et al. J. Geophys. Res.* **111,** A04218 (2006).
7. Chen, Y., Reeves, G. D. & Friedel, R. H. W. *Nature Phys.* **3,** 614–617 (2007).

SUPERFLUID DYNAMICS

Vortices on the scales

Beautiful as they are, and useful as their concept is (see, for example, Keith Burnett's News & Views article on page 589 of this issue), vortices remain elusive in many respects. David Thouless and James Anglin have turned their attention to vortices in superfluids — in these, vortices are quantized, meaning that the circulation around a closed loop can take only discrete values — and revisit the question of vortex inertial mass (*Phys. Rev. Lett.* (in the press); preprint at http://arxiv.org/abs/cond-mat/0703523; 2007).

The inertial mass of a vortex is an important parameter in understanding its dynamics. But, so far, there seems to be no agreement in the literature on how this mass should be defined when dealing with a superfluid. Although Thouless and Anglin reconcile aspects of earlier approaches, they conclude that the mass


GETTY

of a vortex might not be well defined at all; rather, it depends on the way it is measured. Or, put another way, inertial effects in vortex dynamics might depend on the context in which they occur.

Earlier definitions of the mass of a vortex in a superfluid — such as basing it on the energy required to form a vortex at rest — were mostly indirect. Thouless and Anglin follow a more direct route, and propose measuring the inertial mass by driving the vortex around in circles. The required handle on the vortex could be provided by an external potential that 'pins' it. When the potential is then moved around in a circular orbit, dragging the vortex with it, the mass can be derived from the force on the accelerated vortex.

In the specific framework considered here, the Gross–Pitaevskii model for superfluids, a simple expression for the vortex mass is found. But the study also shows that the mass depends on the form of the pinning potential, suggesting that, after all, an unambiguous vortex mass might not be decipherable.

Andreas Trabesinger