Acceleration of killer electrons
Richard Bertram Horne

It is almost 50 years since the Van Allen radiation belts were discovered by Explorer I, the first US satellite put into orbit. Trapped in the Earth's mag–netic field and encircling the Earth like a ring doughnut, the number of electrons travelling at relativistic velocities within these belts can vary by up to five orders of magnitude within just a few days, or even minutes. Such extreme fluctuations are known to be caused by a combination of mechanisms taking place within the geomagnetic field, but the exact mechanism by which electrons are accelerated from energies of the order of a few keV to several MeV has long been a puzzle. In recent years, two leading theories have emerged to explain this. The first involves a process of radial diffusion: electrons diffuse towards the Earth as a result of large-scale electric and magnetic field fluctuations in the outer belt, and are accelerated by betatron and Fermi processes1,2. And the second involves local wave-particle interactions, in which electrons are accelerated by gyro-resonance with waves that propagate through the heart of the radiation belts3,4. Evidence supporting both mechanisms was provided during a rare and unusual magnetospheric event that has come to be known as the 2003 Hallowe'en geomagnetic storm5,6. On page 614 of this issue, Chen and colleagues7 now break this theoretical deadlock, to report definitive observational evidence that supports gyro-resonant wave interactions as the dominant process of relativistic electron acceleration.

According to the radial diffusion model, electrons are transported to within 2.5 Earth radii (Re) during magnetic storms from a reservoir of particles beyond geostationary orbit at 6.6 Re. As with any diffusion theory, there must be a gradient in the distribution of particles, and some mechanism by which the particles are scattered. But in the magnetosphere collisions between particles are rare, and scattering across the magnetic field is most effective when there
are electromagnetic waves at frequencies of a few millihertz that match the frequency at which electrons drift around the Earth. Moreover, for diffusion to be directed inwards towards the Earth, the gradient in electron phase-space density (which is proportional to the measured flux divided by the square of the electron momentum) must increase outwards. Using two years of data collected by multiple satellites at several different locations in the magnetosphere, Chen *et al*. find that peaks in the electron phase-space density are most commonly observed near 5.5 Re, near the centre of the outer belt. These peaks are inconsistent with inward radial diffusion from a source
beyond geostationary orbit. Instead, they strongly suggest that there is local acceleration near 5.5 Re, and that radial diffusion actually transports electrons away from the Earth, beyond the radiation belts.

In contrast to radial diffusion, which necessarily acts over large distances of the order of 1 Re, gyro-resonant wave acceleration is the most effective form of localized acceleration within the magnetosphere. By this mechanism, the sporadic injection of particles originating from the solar wind and, through other complicated multistage acceleration processes, the ionosphere, cause an anisotropic distribution of particles and excite a variety of different types of electromagnetic waves. Of these, so-called 'whistler mode chorus waves' undergo some of the strongest interactions with relativistic electrons. The relative motion of such waves and injected particles along magnetic field lines induces a Doppler shift of the wave frequency, causing it to converge to the same frequency at which the electrons gyrate in the magnetic field — an effect known as gyro-resonance. This in turn causes the electrons to diffuse 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 observations7 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).