Cold ions in the hot plasma sheet of Earth's magnetotail

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Most visible matter in the Universe exists as plasma. How this plasma is heated, and especially how the initial non-equilibrium plasma distributions relax to thermal equilibrium (as predicted by Maxwell–Boltzman statistics), is a fundamental question in studies of astrophysical[1–3] and laboratory plasmas[4,5]. Astrophysical plasmas are often so tenuous that binary collisions[2,3] can be ignored, and it is not clear how thermal equilibrium develops for these 'collisionless' plasmas. One example of a collisionless plasma is the Earth's plasma sheet[6], where thermalized hot plasma with ion temperatures of about 5×10^7 K has been observed[7]. Here we report direct observations of a plasma distribution function during a solar eclipse, revealing cold ions in the Earth's plasma sheet in coexistence with thermalized hot ions. This cold component cannot be detected by plasma sensors on satellites that are positively charged in sunlight, but our observations in the Earth's shadow show that the density of the cold ions is comparable to that of hot ions. This high density is difficult to explain within existing theories[8–10], as it requires a mechanism that permits half of the source plasma to remain cold upon entry into the hot turbulent plasma sheet.

Plasma is composed of an assembly of charged particles and is often referred to as the fourth state of matter because of its distinctive collective behaviour while maintaining charge neutrality. Plasma is quite common in the universe: most celestial objects and the interstellar medium are in the plasma state. A special feature of the plasma state is its wide variety of wave modes that enable effective energy transfer between ions, electrons and wave fields through various microscopic and macroscopic instabilities. This energization via waves can contribute to thermalization of the plasma, even if binary collision frequencies between constituent particles are much lower than the timescale of phenomena of interest.

In the nightside region of near-Earth space, a large-scale region called the plasma sheet (Fig. 1a) is formed through interaction between the intrinsic terrestrial magnetic field and the solar wind (a supersonic plasma flowing from the Sun). The plasma sheet lies between the northern and southern lobe regions characterized by strong magnetic field and cold (a few tens of electronvolts, eV) plasma. The cold plasma from the lobes becomes energized at the boundary layer between the plasma sheet and lobes, thereby forming the hot plasma sheet. The existence of this hot plasma sheet is thus observational evidence for the creation of thermalized hot plasma without collisions. Stimulated by the observations, plasma physicists have proposed a variety of acceleration and heating mechanisms for ions and electrons in the boundary layers of the plasma sheet[8–10]. While the relative importance of each heating mechanism remains to be established, these theories predict that the originally cold source plasma cannot remain cold in the plasma

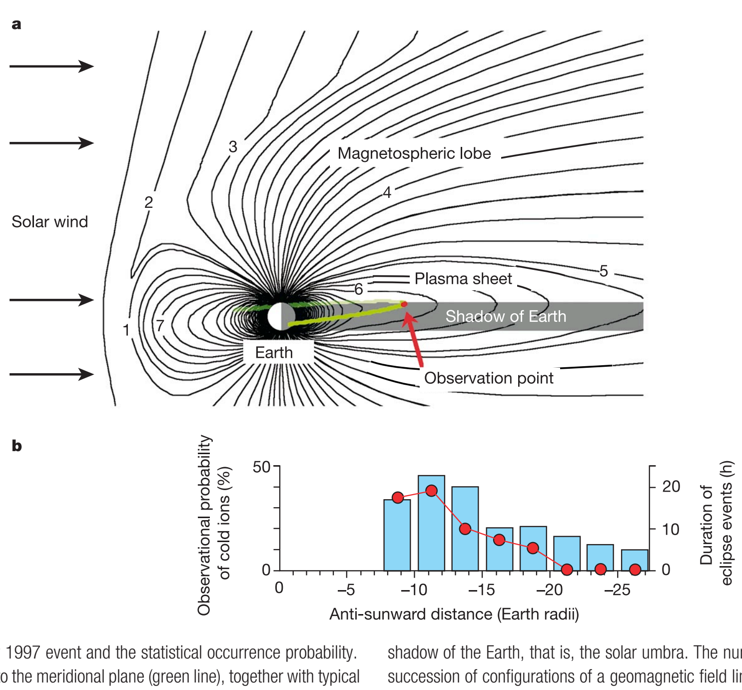

Figure 1 Location of the 19 July 1997 event and the statistical occurrence probability. **a**, Projection of GEOTAIL orbit onto the meridional plane (green line), together with typical magnetic field configuration during periods of southward interplanetary magnetic field. The Earth is indicated with a circle, the left-hand side of which corresponds to the direction towards the Sun. The red point shows the position where GEOTAIL entered the shadow of the Earth, that is, the solar umbra. The numbered field lines illustrate the succession of configurations of a geomagnetic field line during magnetospheric convection. **b**, Probability of cold-ion detection in the plasma sheet from GEOTAIL eclipse data in 1995–1998 (red circles) together with total duration of eclipse events per bin of distance (blue bars) is shown as a function of distance from the Earth.