SAR arcs

The midlatitude stable red auroral (SAR) arcs are well known examples of **electron heating** in the upper F - region (400 km) of the Earth's ionosphere that produces red aurora (see low-latitude aurorae). The Te (electron temperature) enhancement produces the red (typically subvisual) 630.0 nm emission of these events by exciting the lowest electronic state in atomic oxygen, O(1D). Temperatures of several thousands Kelvins have been measured in SAR arcs. The energy source is the heat conduction from the magnetosphere.

SAR arcs are rather stable phenomena compared to discrete aurora and, when modeling the phenomena, a steady state electron energy equation can be used. In the 300-500 km altitude interval the principal energy loss mechanisms are

- excitation of the fine structure levels of O
- vibrational excitation of N2
- elastic collisions with ambient O+ ions
- excitation of O(1D)

It is usually assumed that Te = Ti = Tn at the lower boundary, about 100 km altitude, and a heat flux, a temperature gradient, or a temperature is specified at the upper boundary, about 1000 km. The loss rate, Le, contains Te, Tn, Ti, ion densities and neutral densities, and thus the energy equation and continuity equation must be solved self-consistently.
The ultimate energy source of SAR arcs can be found in the magnetospheric ring current region. At least three different theories have been proposed (see, e.g., Kozyra *et. al*., 1987; Fok*et. al*., 1991):

1. Coulomb collisions between ring current protons and thermal electrons
2. Landau damping by thermal electrons of ion cyclotron waves generated by the anisotropic ring current ion distributions
3. Resonant damping of kinetic Alfven waves

Also collisionless damping of electromagnetic ion cyclotron waves have been considered by Konikov and Pavlov, 1991. The first one and its modifications have been the ones discussed mostly. In the first two mechanisms the energy is transported from the magnetosphere along magnetic field lines down to F - region heights via some form of heat transport in the thermal electron gas or via a low-energy (few eV) precipitating electron flux. Since SAR arcs occur in the low-density trough region, this energy input is distributed among fewer electrons than in the surrounding area and can result in highly elevated electron temperatures. This is the main reason for the often seen anticorrelation between electron temperatures and densities (e.g., Evans *et. al*., 1983; Breen *et. al*., 1990). Note also that all the cooling reactions are proportional to ne!

The Coulomb collisions between ring current protons and plasmaspheric cold electrons proved to be too inefficient to produce the energy needed. However, the finding of heavier ions in the ring current changed the situation, since they actually dominate the low-energy (E<17 keV) portion of the ring current in the plasmapause region. It made the ring current O+ potentially the major source of SAR arc energy (Kozyra *et. al*., 1987). During the expansion phase of the magnetic substorm the plasmasphere becomes smaller as the plasmapause moves to lower L shells (L = 2-4) due to the enhanced cross-tail potential. As the recovery phase proceeds, the plasmasphere begins to refill over the energetic ring current. Thus a region of overlap develops between the enhanced (due to substorm injections) ring current and cold plasmaspheric population, making extensive Coulomb collision rates between O+ and electrons possible. This region of overlap maps along field lines to low altitudes in the SAR arc region of the subauroral ionosphere. It is also possible that a feedback phenomenon occurs: formed positive temperature gradient along the field lines could lead to upward flow of minor heavy ions (like O+) due to thermal diffusion, and thus increase plasmapheric heavy ion concentration (forming heavy ion torus/shell?). At least measurements by DE 1 and 2 show close association between plasmaspheric O+ and/or O++ density enhancements and ionospheric Te peak (Horwitz*et. al*., 1986).

Figure: Example of nearly simultaneous DE-1, DE-2, and Chatanika radar measurements. The inner plasmapause region seen in DE-1 density measurements is colocated with signatures in Te measured by DE-2 (from Green et. al., 1986).

A general association between subauroral Te peaks and plasmaspheric density gradients have been seen, making them more reliable low-altitude plasmapause signatures than electron density changes (mid-latitude troughs; see, e.g., Green *et. al*., 1986). This can be seen also in the Figure. Note that the Te signature coincides with the inner plasmapause, i.e., it never shows the dusk bulge characteristic of the equatorial plasmasphere. The Te peaks correlate also with ionospheric ne troughs (e.g., Watanabe *et. al*., 1989), although this is not very well seen in the Figure (probably because of the high altitude; note that the main ionospheric trough is, at least in the evening sector, clearly poleward of the plasmapause). The often seen sharp poleward edge in the latitudinal profile of Te enhancements can be explained by the drop in heat capacity and reduction in the coefficient of heat conductivity, both of which are results of the corresponding drop in density at the plasmapause, particularly at the inner plasmapause (Brace *et. al*., 1988). In addition, the magnitude of the subauroral Te peak , which is an indication of the amount of energy transferred to the ionospheric electrons from the magnetospheric heat source, shows an interesting behaviour. Although the electron densities at equinox are, on average, about 2.5 times higher than those of solstice, there is no seasonal variation to be seen in Te peaks (Fok *et. al*., 1991). This implies compensating changes in the magnetospheric heat source, and actually similar seasonal changes in the magnetospheric O+ content have been measured. Of course this is easy to explain if the O+ ions of the ring current originate from the ionosphere. The magnitude of the Te peaks are naturally also related to the magnetic activity (Dst index, see Fok et. al., 1991).

Actually there is also another possible heat source in the nighttime mid-latitude ionosphere, namely the photoelectron energy that is stored in the plasmasphere during the daytime. The best way to separate these sources (ring current versus photoelectrons) would be to study a series of Te profiles taken over 2- or 3-day period during heating events, since the photoelectron component is much more steady and predictable (Brace et. al., 1988). In addition, it is possible that the heating is due to photoelectrons produced continuously in the conjugate hemisphere, which is sunlit (Evans *et. al*., 1983, Rodger *et. al*., 1986). The latter is an important heat source during winter time (Fok et. al., 1991), weakening the response of the magnitude of the Te peak to magnetic activity.

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