Auroral Precipitation Caused by Auroral Kilometric Radiation

W. Calvert

Department of Physics and Astronomy, University of Iowa, Iowa City

If the auroral kilometric radiation were generated by loss cone lasing on closed field lines, as has been proposed, then it should cause substantial auroral precipitation by the pitch angle scattering of energetic electrons into the loss cone. A rough estimate for this precipitation, based upon the observed auroral kilometric radiation (AKR) amplitudes, would imply a flux of at least $2 \times 10^8$ el/cm$^2$ s over the projected ionospheric footprint of an individual laser and, if most of the AKR radio lasers occupied the same electron drift an L shell, an arc of 8 km width with a minimum average flux of roughly $10^8$ el/cm$^2$ s. It is believed that this will account for auroral arcs and other aspects of auroral electron precipitation.

It has been proposed that the auroral kilometric radiation (AKR) originates from natural radio lasing [Calvert, 1982]. It has also been proposed that the free energy for the instability driving those lasers comes from the energetic electron loss cone [Wu and Lee, 1979]. If these are so, and the pertinent auroral field lines are closed to the conjugate hemisphere, then the generation of the AKR must cause auroral electron precipitation, since loss cone lasing should cause the pitch angle scattering of energetic electrons into the loss cone, where those electrons would automatically have to precipitate. In this paper I shall estimate the precipitation which should occur based upon the apparent size and power of the observed AKR radio lasers.

The apparent length of the AKR radio lasers (W) has already been determined from the observed spectral spacing of their longitudinal modes [Calvert, 1982], and it was found to be approximately 25 km (depending upon the assumed source refractive index). According to straightforward laser theory [Verdeyen, 1981], the width of the wave field inside a lasing laser depends primarily only upon this dimension. For the fundamental transverse mode, where the internal wave field and the emitted beam are both of Gaussian shape, this width is given by

$$a_0 = \left(2\lambda W/\pi \right)^{1/2}$$

(1)

where $a_0$ is measured to the l/e power points and $\lambda$ is the wavelength. For a 1-km wavelength this would give a laser such as that illustrated in Figure 1, having an exit spot width of about 4 km.

The corresponding angular beam width, also measured to the l/e power points, is given by

$$\beta = \left(2\lambda W/\pi \right)^{1/2}$$

(2)

This would give a 9° beam width, and upon correcting for compression of the beam by wave refraction as it escapes, an emission solid angle of about 0.005 sr. Multiplying this by the peak AKR power flux of 1 MW/sr deduced from the IMP 6 observations of Gurnett [1974], this gives a total beam power of about 5 kW [Calvert, 1984]. For a total average power of 40 MW [see Gallagher and Gurnett, 1979], the AKR must consist of about 8000 such laser beams, all at different frequencies and altitudes throughout the AKR source region.

(Equations (1) and (2) can be derived by equating the size of a Gaussian illumination pattern to that of its own diffraction pattern at the opposite end of the laser, since the wave field within a laser must reproduce itself. Otherwise, it can be deduced directly from Verdeyen's [1981, p. 60] equation 3.22.)

Since the AKR lasers are presumably oriented perpendicular to the source magnetic field, the loss cone free energy which is driving them would come either from below, as is illustrated in Figure 1, or from the conjugate hemisphere. As a result of the lasing (and also causing it) the incoming loss cone should emerge from the laser at least partially filled by pitch angle scattering, and it is this filling which causes the proposed auroral precipitation. Occurring over an area of 100 km$^2$, such pitch angle scattering into the loss cone would have to contribute approximately 50 W/km$^2$ to the emitted beam, since it is this scattering into the loss cone which actually provides the emitted AKR energy.

To the extent that the lasers are powered by the loss cone, therefore, this would cause flux of electrons into the loss cone of

$$\Phi = 50E\eta \text{el/km}^2$$

(3)

where $E$ is the electron energy in joules and $\eta$ is the fraction of the electron energy which is given up to the wave. Since $\eta$ cannot be greater than 1, the precipitation flux for kilovolt electrons would then have to be greater than $3 \times 10^7$ el/cm$^2$ s measured at the laser. Projected into the ionosphere, where the magnetic field is about 6 times stronger, this would imply a flux of at least $2 \times 10^8$ el/cm$^2$ s over the projected area of a laser.

If one further assumes that the AKR radio lasers are oriented perpendicular to and distributed along an electron drift L shell, as certain of the AKR observations would seem to suggest [Calvert, 1987], then that would produce an arc of precipitation having a width W determined by the laser length. For a 2000-km evening sector arc spanning the region where the AKR seems to originate, this would imply a projected width of 8 km and an average of perhaps eight overlapping lasers at each longitude, since the projected footprint of an individual laser would then be approximately 8 km in latitude by 2 km in longitude. Counting both hemispheres, this would give a minimum average precipitation flux of about $10^7$ el/cm$^2$ s.
To recapitulate: If the AKR is attributed to loss cone lasing on closed field lines, with the lasers powered by kilovolt electrons, producing 5 kW, and having a length of 25 km, then that should cause a laser-induced precipitation flux of at least $2 \times 10^8$ el/cm$^2$ s over the 8 km x 2 km ionospheric footprint of an individual laser. Moreover, if most of the apparently 8000 lasers producing the AKR occupied the same electron drift L shell, then that could supply an evening sector arc of electron precipitation having a width of about 8 km and a minimum average flux of about $10^9$ el/cm$^2$ s.

As stated elsewhere [Calvert, 1986], the above precipitation should also reduce the source plasma density, since it presumably represents an unreplenished loss to the source. Provided the source contains mostly energetic electrons with a total column content of around $10^{10}$ el/cm$^2$ (based on an initial density of roughly 2 el/cm$^3$ and a field line length of eight earth radii), this density decrease should occur within approximately $10^{10}/3 \times 10^7 = 300$ s or 5 min for an individual laser, and for the precipitation arc which I have postulated, within only about 1 min. Moreover, because of the expected energy spread of the electrons being precipitated, this density decrease should spread itself along electron drift L shells to create a thin sheet of reduced density, within which, because of the increased wave gain and feedback which this would cause, one would expect the lasing to promulgate itself. It is therefore proposed that the AKR radio lasers occur preferentially along the same electron drift L shells by mutually reducing their own source plasma density, and that they would preferentially orient themselves across these shells for the same reason, by creating their own L-shell-aligned density mirrors.

Although still requiring a plasma which is energized by some other means, this raises the possibility that the emission of the AKR by radio lasing actually causes the discrete auroral arcs with which it is associated [Gurnett, 1974; Voots et al., 1977]. If this were so, as is illustrated schematically in Figure 2, the width of an arc would be attributed to the optimum size which is required for lasing (which cannot be too large because of diffraction losses, nor too small for the want of sufficient gain), whereas its extension in longitude would be attributed to a longitudinal spread of the resulting density depletion along electron drift L shells.

It must be emphasized that the above estimates represent an extreme lower limit for the precipitation which should occur, based upon the emission of AKR with 100% efficiency. Since the actual emission efficiency could obviously be much less than this, the actual precipitation could be much greater, and the time scales for forming an organized arc, correspondingly shorter. For instance, if the actual emission efficiency (with respect to the precipitating electrons) were as small as 1% or less, as the apparent ratio of the AKR and auroral energies would suggest [Gurnett, 1974], then the expected precipitation could be 100 times greater. This means that the precipitation flux of a single laser could be as large as $10^{10}$ el/cm$^2$ s, and the average for an arc, over $10^{11}$ el/cm$^2$ s. In view of the uncertainties and variabilities of both the aurora and the AKR, this certainly represents adequate agreement with the observed auroral electron fluxes [Hultqvist, 1973].

Since the pitch angle scattering should occur regardless, as long as the AKR is powered by the loss cone, the overall auroral electron precipitation might have been accounted for on this basis without the concept of lasing. This, however, would not give the localized precipitation which occurs in the aurora, nor would it give the very intense wave electric fields (of 20–200 mV/m, according to previous estimates [Calvert, 1982]) which would be required to scatter an electron significantly during a single pass through the thin source region depicted in Figure 1. (Lasing, on the other
hand, guarantees this automatically because of the inevitable gain saturation which must occur, since that immediately implies that a laser must produce wave amplitudes which are sufficient to deplete the available free energy.) Moreover, it is suspected that the emission efficiency for linear amplification would be far less than even the 1% previously mentioned, in which case the predicted overall electron precipitation would be vastly greater than that which is observed. I would therefore expect that the inherent high efficiency of lasing would be required so as not to exceed the observed auroral precipitation, and hence that this could become yet another argument in favor of the lasing hypothesis.

Be that as it may, I consider that there is already ample evidence that the AKR must be generated by lasing, from its discrete multiple spectrum [Gurnett and Anderson, 1981; Calvert, 1982], its angular coherence [Baumback et al., 1986], and its monochromaticity [Baumback and Calvert, 1987]. Besides, for the purposes of this paper the laser hypothesis is not at question. It was introduced as a premise, and the results are cast as a consequence of that premise, in the belief that this was the nature of the AKR emitters as they exist, according to their radio signature. Although the argument could be applied in either direction, the resulting explanation for auroral arcs which has been presented here is simply that, an explanation for the arcs, and not offered primarily as further evidence for the lasing.

The deduction of an auroral arc width of approximately 8 km is a specific prediction of the laser precipitation model. Also predicted by that model would be finer structure along the arc of roughly 2 km thickness corresponding to the transverse dimension of a fundamental-mode laser, as well as even finer periodic structures with similar spacings corresponding to the higher-order transverse modes which can also occur. What I have just described would correspond to a homogeneous arc, an auroral ray, and a rayed band, as described by Omholt [1973]. The radio laser precipitation model could thus account for various phenomenological aspects of the aurora which have hitherto lacked concrete explanation, and it could do so with the correct order of magnitude for their dimensions.

What one should see in an auroral arc, viewed with sufficiently fine spatial and temporal resolution, is an overlapping pattern of rays, presumably varying and moving on time scales comparable to those of the AKR discrete emissions (of seconds to a few minutes), with each ray elongated perpendicular to the arc by ratios of 4:1 or more, depending upon which of the transverse laser modes are excited. What one actually does see, in the excellent auroral images of Ono et al. [1987] and M. Ejiri and T. Hirasesawa (private communication, April 1987), is precisely that, although I am not at liberty to reproduce their results.

If the concept of laser-induced auroral precipitation proves correct, as I am certain it will for reasons beyond those presented here, it should clearly revolutionize auroral research, since it constitutes a radical departure from the conventional wisdom which would attribute auroral precipitation to externally imposed field-aligned currents and localized electron acceleration. Its principal impact will be to separate the phenomenon of precipitation from that of electron energization and to remove the need for the latter to account for the detailed pattern of electron deposition. It will also open many new concerns about auroral electrodynamics and many new questions about the auroral observations which have heretofore been interpreted differently.

Acknowledgments. This work was supported by NASA contract NGL-16-001-043 and developed from the author's analysis of the AKR radio observations over the past nine years, with ISIS 1, Hawkeye, IMP 6, ISEE 1, and DE 1, partly under NASA contracts NAS5-310 and NAS5-28701 and NASA grant NAGW-256. R. L. Huff is thanked for his encouragement.

The Editor thanks M. L. Kaiser and another referee for their assistance in evaluating this paper.

REFERENCES


Calvert, W., An explanation for triggered auroral kilometric radiation, the auroral plasma cavity, and discrete auroral arcs (abstract), Eos Trans. AGU, 67, 1158, 1986.


W. Calvert, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242.

(Received December 1, 1986; revised May 19, 1987; accepted May, 22, 1987.)