

A Correlation Between Auroral Kilometric Radiation and Field-Aligned Currents

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Simultaneous observations of field-aligned currents (FAC) and auroral kilometric radiation (AKR) are compared from the polar-orbiting satellites Triad and Hawkeye. The Triad observations were restricted to the evening-to-midnight local time sector (1900 to 0100 hours magnetic local time) in the northern hemisphere. This is the region in which the most intense storms of AKR are believed to originate. The Hawkeye observations were restricted to when the satellite was in the AKR 'emission cone' in the northern hemisphere and at radial distances $\geq 7 R_E$ (earth radii) to avoid local propagation cutoff effects. A $(R/7R_E)^2$ normalization to the power flux measurements of the kilometric radiation from Hawkeye is used to take into account the radial dependence of this radiation and to scale all intensity measurements so that they are independent of Hawkeye's position in the emission cone. Integrated field-aligned current intensities from Triad are determined from the observed transverse magnetic field disturbances. There appears to be a weak correlation between the AKR intensity and the integrated current sheet intensity of field-aligned currents. In general, as the intensity of auroral kilometric radiation increases so does the integrated auroral zone current sheet intensity increase. Statistically, the linear correlation coefficient between the log of the AKR power flux and the log of the current sheet intensity is 0.57. During weak AKR bursts ($< 10^{-18} \text{ W m}^{-2} \text{ Hz}^{-1}$), Triad always observed weak FAC's ($< 0.4 \text{ A m}^{-1}$), and when Triad observed large FAC's ($\geq 0.6 \text{ A m}^{-1}$), the AKR intensity from Hawkeye was moderately intense (10^{-15} to $10^{-14} \text{ W m}^{-2} \text{ Hz}^{-1}$) to intense ($> 10^{-14} \text{ W m}^{-2} \text{ Hz}^{-1}$). It is not clear from these preliminary results what the exact role is that auroral zone field-aligned currents play in the generation or amplification of auroral kilometric radiation.

1. INTRODUCTION

From satellite observations, intense electromagnetic radiation at kilometric wavelengths has been found to escape outward from the earth's auroral zone. This radiation has been called auroral kilometric radiation, or AKR, since a considerable amount of evidence indicates that it is generated by auroral particle precipitation during geomagnetic substorms. Auroral kilometric radiation has been found by many authors [Dunckel *et al.*, 1970; Gurnett, 1974; Kaiser and Alexander, 1977; Voots *et al.*, 1977] to be associated with the auroral electrojet current that flows parallel to the earth at auroral zone latitudes in the ionosphere. However, the real need is to determine the relationship between the intensity of auroral kilometric radiation and the field-aligned currents (FAC) flowing along the geomagnetic field into and out of the auroral zone, since auroral kilometric radiation has recently been correlated with fast streams of precipitating auroral electrons [see Benson and Calvert, 1979; Green *et al.*, 1979; Benson *et al.*, 1980]. This relationship may be helpful in developing a better understanding of how auroral kilometric radiation is generated and the role it plays in the dynamics of magnetospheric substorms. In addition, if auroral kilometric radiation is correlated with auroral zone field-aligned currents, an important link may be established between the Io-enhanced Jovian decametric emissions and field-aligned currents, which are believed to exist between Io

and Jupiter, since it is widely held that auroral kilometric radiation is the terrestrial counterpart to the Jovian decametric emissions.

The purpose of this paper is to study the relationship between the power flux of auroral kilometric radiation observed by the eccentric orbiting Hawkeye spacecraft and field-aligned currents deduced from the magnetometer measurements of the low-altitude polar orbiting Triad spacecraft. The Triad magnetometer experiment has been described by Armstrong and Zmuda [1973], and the Hawkeye plasma and radio wave experiment has been described by Kurth *et al.* [1975].

2. OBSERVATIONS OF FIELD-ALIGNED CURRENTS FROM TRIAD

The field-aligned currents used in this study are determined from triaxial flux gate magnetometer measurements taken by the Triad spacecraft over College, Alaska. Launched on September 2, 1972, into a circular polar orbit of 800-km altitude, Triad is gravity-gradient stabilized and thus has a spin period of one revolution per orbit. Triad magnetometer measurements were used to determine the large-scale structure of field-aligned currents flowing into and out of the ionosphere [see, e.g., Iijima and Potemra, 1978, Figure 13]. The field-aligned currents were observed at all magnetic local times in what is believed to be current sheets that are oriented nearly along constant invariant latitude. In contrast, the intense auroral kilometric radiation is generated on the nightside between 1900 and 0100 hours magnetic local time (MLT) and in the auroral zone near 70° invariant latitude [see, e.g., Alexander and Kaiser, 1976; Gallagher and Gurnett, 1979].

It is important to note that several characteristics distinguish the field-aligned currents in the Harang discontinuity sector (2000–2400 MLT) from those observed at other local times [see Iijima and Potemra, 1978; Rostoker *et al.*, 1975].

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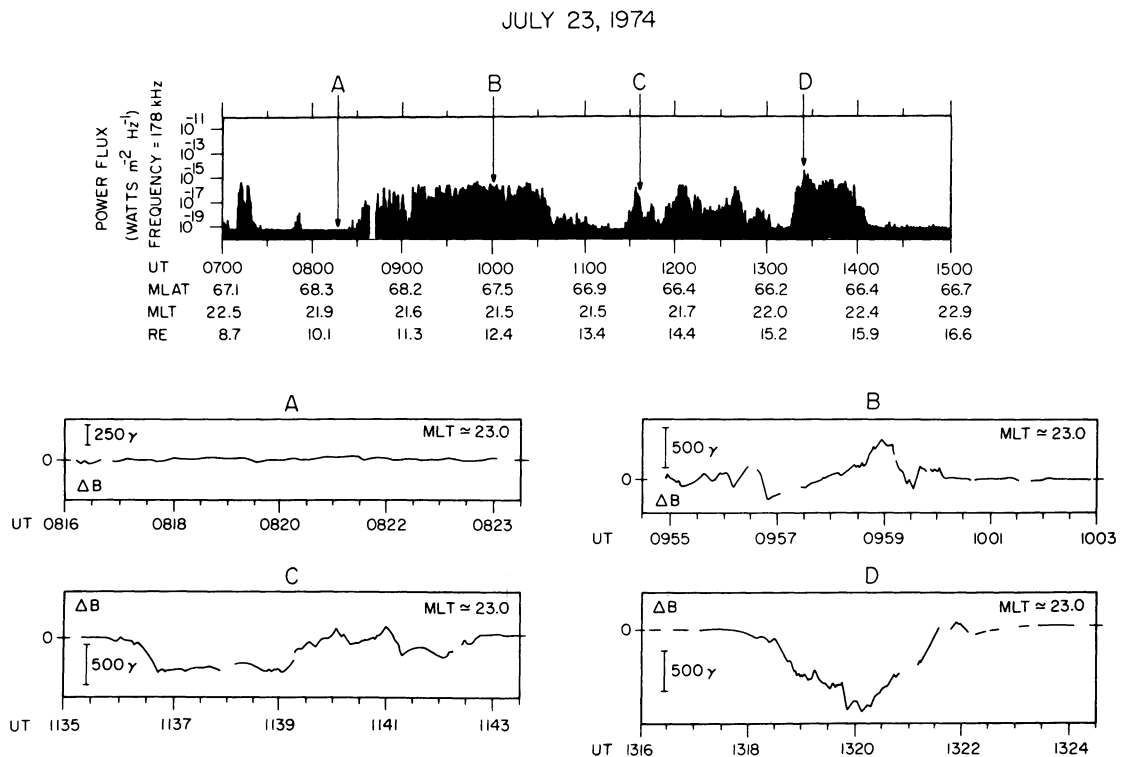


Fig. 1. The top panel shows electric field measurements as a function of time from the Hawkeye satellite while it is in the AKR emission cone during four consecutive passes of the Triad spacecraft through the auroral oval in the northern hemisphere. The Triad magnetometer measurements from the A sensor plotted with respect to the baseline formed by $B_M - B_T$ are shown in the bottom panels A, B, C, and D. Note that when Triad observes large deflections in the magnetic field due to field-aligned currents, Hawkeye observes intense kilometric radiation (times B, C, and D), but when little disturbances in the auroral zones are found (panel A), Hawkeye does not detect AKR above the receiver's threshold.

During undisturbed periods, the field-aligned current flow is often characterized by three basic overlapping regions: namely, a region of current flow away from the auroral ionosphere surrounded on the poleward and equatorward sides by regions of current flow into the ionosphere. During disturbed periods (for example substorms) the field-aligned currents are highly variable and develop complicated features.

Multiple current sheets develop in this sector, and pairs of field-aligned currents appear at higher latitudes, separated from the large-scale system to the south. These characteristics are closely related to the development of the westward electrojet in this sector. For the purposes of this study only, the Triad measurements from 1900 to 0100 MLT will be used since this is the region where the most intense kilometric radiation is generated and the most complicated pattern of field-aligned currents is found.

The determination of field-aligned currents from Triad magnetometer data has been carefully presented by *Zmuda and Armstrong* [1974]. Briefly, the magnetic disturbance (ΔB) or deflection from the geomagnetic field that is observed by Triad during an auroral zone pass is proportional to the integrated current intensity (J) across a current sheet. Thus

$$J = 8 \times 10^{-4} (\Delta B)$$

where ΔB is measured in gammas and J is in amps per meter. Only the largest integrated current intensity for each Triad pass is used in this study to characterize the in situ auroral

zone field-aligned currents since multiple current sheets are not uncommon.

3. AKR OBSERVATIONS FROM HAWKEYE

The Hawkeye spacecraft provided observations of auroral kilometric radiation up to 46 hours per 52-hour orbit from launch on June 3, 1974, until it reentered the atmosphere on April 28, 1978. Hawkeye was in a highly eccentric earth orbit of about 89° inclination with an apogee radial distance of nearly $22 R_E$ (earth radii) in the northern hemisphere. The angular distribution of auroral kilometric radiation at 178 kHz was determined by *Green et al.* [1977] from Hawkeye electric field observations. The back shading in Figure 4 of *Green et al.* [1977], termed the AKR emission cone, is the region of magnetic latitude and magnetic local time where Hawkeye has the highest probability of observing auroral kilometric radiation if it is being generated. The simultaneous observations used in this study are selected from the times when Hawkeye is in the AKR emission cone at radial distances $\geq 7 R_E$ (to avoid local propagation cutoff effects; see *Green et al.* [1977]) and when Triad is in the auroral oval from 1900 to 0100 MLT in the northern hemisphere.

4. A CORRELATION BETWEEN AURORAL KILOMETRIC RADIATION AND FIELD-ALIGNED CURRENTS

Between June 1974 and August 1975 there were 257 Triad auroral zone passes (from 1900 to 0100 MLT) while Hawkeye was in the AKR emission cone. Some typical simultaneous measurements from Hawkeye and Triad are illustrat-

ed in Figure 1. The top panel of Figure 1 shows electric field intensities in units of power flux at 178 kHz from the plasma wave instrument onboard Hawkeye. All the radio emission above the receiver noise level is attributed to auroral kilometric radiation. Simultaneous magnetic field observations made by the Triad spacecraft during four consecutive passes through the auroral zone in the northern hemisphere at about 2300 MLT are shown in the panels marked A, B, C, and D. The magnetic field measurements are from the A sensor onboard Triad and are plotted in terms of ΔB deviation from the baseline formed by $B_M - B_T$. The A panel illustrates that the Triad pass through the auroral zone shows little evidence of east-west field-aligned current sheets. The maximum deviation occurs at about 0816:30 UT with $\Delta B \approx 43$ gammas. Simultaneously, the Hawkeye plasma wave experiment does not detect auroral kilometric radiation (see arrow labeled A in the top panel of Figure 1). Approximately 90 min later on the next pass through the auroral oval in the northern hemisphere the Triad magnetometer experiment revealed an extremely complicated system of east-west field-aligned current sheets which is a typical Triad observation in this magnetic local time sector, see section 2). The integrated current across the major current sheet (0957 to 0959 UT) of the Triad pass in the B panel is 0.52 A/m. Meanwhile, from its position in the emission cone, Hawkeye observed intense auroral kilometric radiation of more than 10^{-16} W/(m² Hz) (see arrow labeled B in the top panel of Figure 1). The integrated current intensity of the field-aligned current sheets at 1320 UT in panel D of Figure 1 is nearly 0.85 A/m, while the AKR power flux, the largest observed for this time period, was greater than 10^{-14} W/(m² Hz). Figure 1 is consistent with the idea that intense auroral zone field-aligned currents are correlated with intense bursts of auroral kilometric radiation.

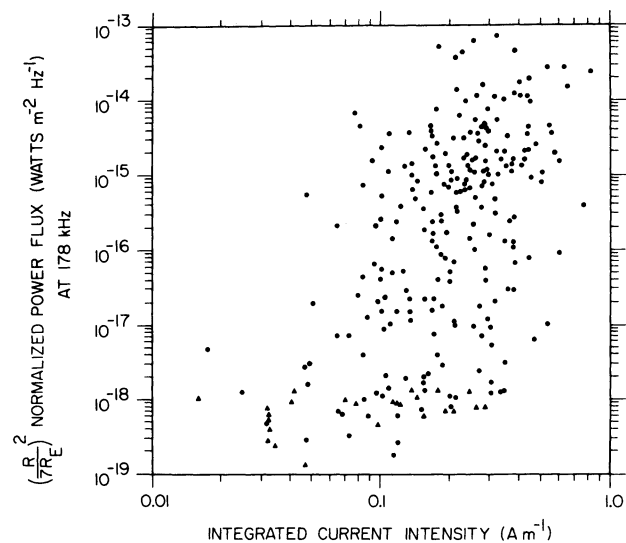


Fig. 2. Simultaneous power flux measurements of AKR at 178 kHz versus the integrated current intensity of auroral zone field-aligned currents. A $(R/7R_E)^2$ normalization to the power flux measurements is applied to take into account the radial dependence of this radiation. The R variable is the distance from the satellite to the average source region of AKR (see text). The triangles represent an upper limit to the power flux, since the kilometric radiation was not detected at those times. A weak correlation can be seen in that, as the power flux increases, so does the integrated current intensity of field-aligned currents.

To provide a qualitative evaluation of the relationship between auroral kilometric radiation and field-aligned currents, Figure 2 is a scatter plot of simultaneous 3-min average AKR power flux measurements at 178 kHz versus the integrated current intensity across the largest current sheets observed on each Triad pass. A 3-min average of the electric field measurements from Hawkeye takes into account any spin modulation effect and gives a power flux determination on a time scale comparable to the complete crossing of Triad across the auroral zone. To take into account the radial dependence of auroral kilometric radiation; a $(R/7R_E)^2$ normalization is applied to the average power flux measurements. The R variable is the distance from the satellite to the average source region of auroral kilometric radiation ($2.5 R_E$ along a 70° invariant latitude magnetic field line at a magnetic local time of 2300, in agreement with *Gallagher and Gurnett [1979]*). The triangles in Figure 2 are the times when auroral kilometric radiation was not detected by Hawkeye above the receiver's noise level and represent an upper limit. A weak correlation can be seen: as the AKR power flux increases, so does the integrated current intensity increase. Statistically, the linear correlation coefficient of the log of the power flux versus the log of the integrated current intensity is 0.57. A random error analysis produces a probability of less than $10^{-7}\%$ in obtaining the 0.57 correlation coefficient from an uncorrelated parent population, illustrating the level of confidence for this correlation. From Figure 2, when the AKR power flux was weak ($<10^{-18}$ W/(m² Hz)), the integrated current intensity was less than 0.36 A/m, while for integrated current intensities greater than 0.6 A/m the AKR power flux was moderately intense (10^{-15} to 10^{-14} W/(m² Hz)) to very intense ($>10^{-14}$ W/(m² Hz)). The correlation in Figure 2 indicates that field-aligned currents may play an important role in the generation of auroral kilometric radiation since the currents are always observed in the auroral zone when Hawkeye observes AKR.

5. POSSIBLE SOURCE OF SCATTER IN CORRELATION BETWEEN AKR AND FIELD-ALIGNED CURRENTS

Several sources of uncertainty and fluctuations could have contributed to the scatter in Figure 2, which we will presently discuss. A detailed study of the distribution of intensity in the AKR emission cone at 178 kHz by J. L. Green and D. L. Gallagher (manuscript in preparation; 1982) revealed that in a coordinate system with the average source region of AKR (used in this study) at the origin, bursts of auroral kilometric radiation uniformly illuminate the AKR emission cone to within much less than 10 dB. Probably the largest source of scatter in Figure 2 is due to using global (power flux) versus local (field-aligned currents) measurements. Triad, on any given pass, cuts through the nighttime auroral oval at nearly constant local time, and it is certain that Triad will not always observe the most intense part of the premidnight field-aligned current system. Hawkeye, however, from its position in the AKR emission cone observes an integrated power flux of auroral kilometric radiation from the entire evening active auroral region. Global versus local measurements could easily produce the scatter in Figure 2 since many intense bursts of auroral kilometric radiation ($>10^{-16}$ W/(m² Hz)) could then be associated with relatively small field-aligned currents (<0.3 A/m), but there are no cases of intense field-aligned currents (>0.6 A/m) associated with weak ($<10^{-17}$ W/(m² Hz)) auroral kilometric bursts. From

the present discussion of the sources of scatter in Figure 2 it is not surprising that a relatively low linear correlation coefficient was found; however, event-by-event cases such as Figure 1 may prove, at this point, to be more convincing.

6. DISCUSSION

It is important to speculate on the role which field-aligned currents might play in the generation and possible amplification of auroral kilometric radiation, as suggested by Figure 2. One direct relationship is that field-aligned currents are probably bringing into the AKR source region the particles or current whose energy, at least in part, is converted into the kilometric radiation. Increases in the integrated current intensities of field-aligned current may be due to progressively larger and larger particle fluxes at progressively higher velocities. Since Triad does not have a particle experiment onboard, the energies and fluxes of the actual precipitating magnetospheric particles and upgoing (out of the ionosphere) ionospheric particles making up the field-aligned current observed are not known. There are only a few examples of the simultaneous observation of the field-aligned current and particle measurements in the literature. The basic result from these studies [see, e.g., *Cassery and Cloutier, 1975*] is that the particle fluxes, in the energy range of the particle detector flown (typically 0.5 to >20 keV), usually account for only 20% or less of the inferred current deduced from the accompanying magnetometer data. This result implies that the majority of the current carriers are particles at low energies (<0.5 keV). The examples given in the literature, however, are usually preliminary and may not reflect the true nature of the current carriers in field-aligned current used in this study since simultaneous currents and particle observations are not always from the magnetic local times 1900 to 0100.

Recent studies [see, e.g., *Green et al., 1979*] indicate that auroral kilometric radiation is correlated with high-velocity (energies from 1 to 18 keV) electron precipitations in the premidnight auroral zone known as inverted-V events. However, if the majority of the field-aligned currents observed by Triad are carried by low-energy particles, then the correlation between AKR and field-aligned currents as shown in Figure 2 may indicate a more indirect relationship. For example, current instabilities producing low-frequency wave turbulence such as electrostatic ion cyclotron waves or ion acoustic waves in the auroral zone have been postulated by *Kindel and Kennel [1971]*. *Kintner et al. [1978]* have observed intense electrostatic ion cyclotron waves (≈ 25 mV/m at 115 Hz) with the S3-3 spacecraft near 2000 MLT at an altitude of more than 6000 km in the auroral zone and found them to be consistent with the current-driven model proposed by *Kindel and Kennel [1971]*. Ion heating due to electrostatic ion cyclotron turbulence has been shown theoretically by *Palmadesso et al. [1974]* to produce anomalous resistivity and, thus, field-aligned potential drops. Field-aligned potential drops, or parallel electric fields, are generally believed to be responsible for the formation and acceleration of inverted-V electron precipitation events which may in some way be responsible for the generation or amplification of auroral kilometric radiation [see *Green et al., 1979*]. Thus Figure 2 may illustrate that increasing field-aligned current intensity increases the growth of the electrostatic ion cyclotron waves enhancing anomalous resistivity, which leads to parallel electric fields and the production of

inverted-V events associated with auroral kilometric radiation. This is a rather idealized interpretation since the process of producing field-aligned potential drops from anomalous resistivity is not related simply to the current intensity. Double layers and electrostatic shocks, which also produce field-aligned potential drops, can be established by a current above a certain threshold. However, the magnitude of the field-aligned potential drop (for inverted-V acceleration) in a double layer or electrostatic shock is determined not from the intensity of the current but from the external generator such as the magnetospheric tail (see, for example, the review by *Goertz [1979]*). From these general considerations of accelerating mechanisms it is clear that the relationship between auroral kilometric radiation and field-aligned currents may be extremely complicated.

There are, in addition to the quantitative results of Figure 2, qualitative features of auroral kilometric radiation and field-aligned currents that deserve mention. The conditions which lead to the generation of auroral kilometric radiation must be easily met since, when Hawkeye is in the AKR emission cone, auroral kilometric radiation is detected above the receiver noise level nearly 90% of the time. Similarly, Triad observes field-aligned currents as a permanent feature of the auroral zone. As easily seen in panels B, C, and D of Figure 1, either much structure exists in the separate current sheets or rapid temporal variations in field-aligned currents exist on a time scale of seconds, or both. The question of whether field-aligned currents exhibit rapid temporal fluctuations or have fine-structured current sheets within current sheets cannot be discerned with the single Triad spacecraft. It is interesting to note, however, that one basic characteristic of auroral kilometric radiation is that rapid fluctuations in the intensity of this radiation, like field-aligned currents, exist on a time scale of seconds and even less than a second [see *Gurnett et al., 1979*].

In summary, Figure 2 illustrates quantitatively that field-aligned currents in the premidnight auroral zone, from this study, are weakly correlated with auroral kilometric radiation such that as the log of the AKR power flux increases so does the log of the integrated current intensity increase. But because of the scatter in Figure 2, perhaps the most convincing evidence for a correlation comes from an event-by-event examination of auroral kilometric radiation and field-aligned currents, as illustrated in Figure 1. It is suggested that field-aligned currents play not only a direct role in the generation of AKR but possibly also an indirect one with the development of parallel electric fields that produce inverted-V electron precipitation which has also been associated with auroral kilometric radiation. It is clear that the exact relationship between AKR and field-aligned auroral currents is far from being understood and that much work is needed in this area. It is hoped that this brief study will serve as a basis for future research when in situ measurements of auroral kilometric radiation, field-aligned currents, and particle precipitation are made (perhaps with Dynamics Explorer), a more unified picture of the generation mechanism of this intense radio emission will be obtained.

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