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for the physics of the plasmapause region

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B E L G I S C H I N S T I T U U T V O O R R U I M T E - A E R O N O M I E

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FOREWORD

This article has been presented at the Symposium on the Physics of the Plasmopause, which was held September 23-26, 1974 in Trieste (Italy) as part of the second meeting of the 'European Geophysical Society'. This article will be published in the *Annales de Géophysiques*.

AVANT-PROPOS

Ce texte a été présenté au Symposium sur la Physique de la Plasmopause qui s'est tenu du 23 au 26 septembre 1974 à Trieste (Italie) dans le cadre de la deuxième réunion de la 'European Geophysical Society'. Ce texte sera publié dans les *Annales de Géophysique*.

VOORWOORD

Volgende tekst werd voorgedragen op het Symposium over de Fysica van de Plasmapauze, dat plaats had te Triëste (Italië) van 23 tot 26 september 1974 als onderdeel van de tweede zitting van de 'European Geophysical Society'. Het artikel zal verschijnen in de *Annales de Géophysique*.

VORWORT

Dieser Text wurden am Symposium über die Physik der Plasmopause der in Triest (Italien) zwischen den 23n und den 26n September, 1974 as Teil der zweiten Versammlung der 'European Geophysical Society', vorgetragen. Dieses Artikel wird in die *Annales de Géophysique* herausgebracht werden.

STABLE AURORAL RED ARCS AND THEIR IMPORTANCE FOR THE PHYSICS OF THE PLASMAPAUSE REGION

by

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Abstract

A Stable Auroral Red arc is a diffuse glowing zone detected in the midlatitude atmosphere during the main phase of a geomagnetic storm. The spectrum, the intensity, the spatial distribution, the frequency of occurrences and the position of these subvisual line emissions are reported. Their close connection with the Plasmopause and Ring Current regions is described. The different theories proposed for the formation of SAR arcs are also reviewed and briefly discussed.

Résumé

L'Arc Auroral rouge (SAR) est une zone d'émission diffuse détectée dans l'atmosphère de latitude moyenne durant la phase principale d'un orage géomagnétique. Le spectre, l'intensité, la distribution spatiale, la fréquence des observations et la position de ces émissions subvisibles ont été résumés. Leur étroite relation avec la plasmopause et le courant annulaire est décrite. On discute également les différentes théories proposées pour la formation des arcs 'SAR'.

Samenvatting

Het rode noorderlicht (SAR) is een zone van diffuse emissies op middelmatige breedtes ontstaan tijdens de hoofdfase van een geomagnetische storm. Het spectrum, de lichtsterkte, de ruimtelijke spreiding, de frequentie der verschijningen en de plaats dezer emissies, onzichtbaar met het bloot oog, worden besproken en samengevat. Hun enge samenhang met de plasmapauze wordt benadrukt. Tevens worden de verschillende theorieën vermeld die het verschijnsel (SAR) trachten te verklaren.

Zusammenfassung

Die 'Stable Auroral Red' (SAR) Bogen sind matte Beleuchtungen die in der Atmosphäre in mittleren Breite während geomagnetische Stürme beobachtet werden.

Das Spectrum, die Intensität, die Verbreitung, die Frequenz der Beobachtungen, und die Lage dieser Linienuströmungen sind beschrieben worden.

Ihre Zusammenhänge mit der Plasmapause, und den 'Ring Current' is beschrieben worden. Die verschiedene Theorien die für die Entstehung der SAR-Bogen vorgeschlagen wurden, sind besprochen worden.

1. INTRODUCTION

This report on Stable Auroral Red arcs (SAR arcs) has been prepared for presentation at the EGS symposium on the Physics of the Plasmapause. The purpose of this paper is to emphasize the importance of SAR arcs in the study of the plasmapause and of the magnetospheric Ring Current. Indeed SAR arcs are detected near the place where the magnetic field lines from the plasmapause region intersect the mid-latitude upper atmosphere, and they can therefore be used as an efficient tool for ground observations of the position of the plasmapause. SAR arcs are also of major interest in the study of the Ring Current particles. These red arc emissions are essentially detected during the recovery phase of geomagnetic storms, a few hours after the magnetosphere has been strongly disturbed by a large increase of the Solar Wind flux.

Since recent reviews on SAR arcs have been published by Nagy *et al.* [1970], Hoch [1973], Roble and Rees [1974] and Pudovkin [1974], we will limit this presentation to a short report which we hope can be useful as an introduction to this interesting problem.

2. OBSERVATIONS

2.1. Spectrum

- a) The radiation of SAR arcs is predominantly a red line emission at λ 6300 and λ 6364, corresponding to the transition of atomic Oxygen from the excited 1D state to the 3P ground level [Barbier, 1958, 1960]. Since the lifetime of the 1D state is about 2 minutes, this forbidden radiative transition can only occur at high altitudes (> 300 km) where the atmosphere is sufficiently rarefied that quenching by collisional deactivation does not occur strongly.
- b) Occasionally, faint emissions at λ 5577 ($^1S - ^3P$ of OI) are also observed with an intensity less than 2% of the principal λ 6300 radiation [Barbier, 1958, 1960, Hoch *et al.*, 1971].

- c) The N_2^+ emissions, for example λ 4278 and the neutral atomic nitrogen line emission λ 5200 are fainter and more rarely observed [Carleton and Roach, 1965; Hernandez, 1972; Hoch *et al.*, 1971]. Although the occasional N_2^+ emissions occur at lower altitudes than the predominant λ 6300 radiation, they occur along the same magnetic field lines [Smith *et al.*, 1972].
- d) Little, if any, Hydrogen line emissions are present in SAR arc spectra.

2.2. Intensity

Photometric measurements of SAR arcs have shown that the intensity varies in a wide range between 10 kR to 50 Rayleighs [Hoch, 1973]. Due to limitations of instrumental sensitivity, very little is known about the occurrence of SAR arcs with intensities less than 50 Rayleighs.

2.3. Morphology

- a) The maximum intensity of the radiation is typically at 380 - 400 km altitude. Its vertical and latitudinal extents are of the order of 200 - 400 km (see Figure 1).
- b) SAR arcs are diffuse with little detailed structure. Unlike the polar auroral arcs, SAR arcs are stable forms, with sluggish temporal variations.
- c) The duration of an SAR arc is seldom less than a few hours and SAR arcs are often observed continuously from dusk to dawn. Sometimes SAR arcs are detected on 2 or 3 consecutive nights after a major geomagnetic storm onset.

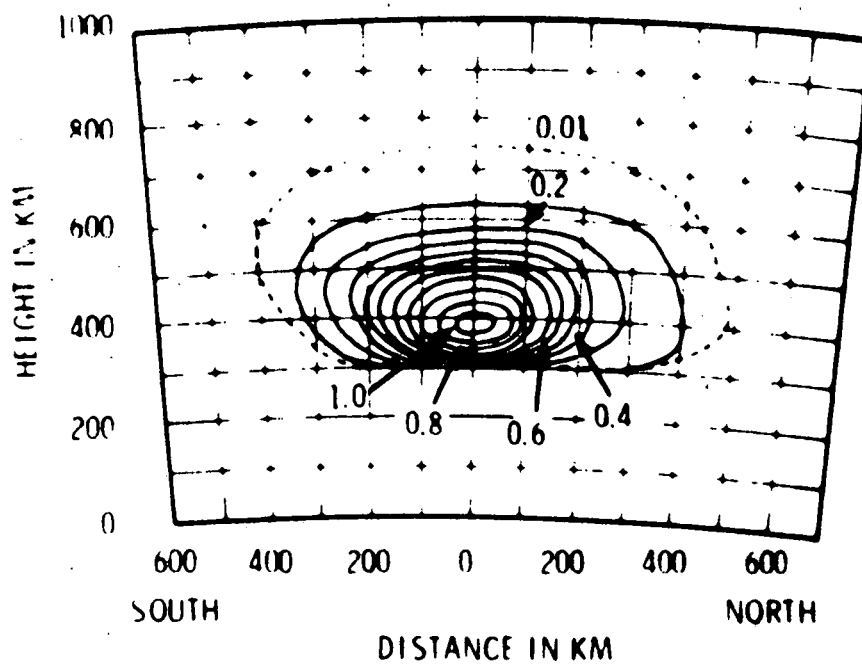


Fig. 1.- Spatial distribution of intensity for an average SAR arc [Tohmatsu and Roach, 1962].

2.4. Position

- a) It was recognized very early that SAR arcs are very extended in longitude and that they are approximately aligned with constant L-shells.
- b) However careful examinations have shown that SAR arcs are often slightly tilted, so that the westward side is at higher L values than the eastward side. The inclination of the arc direction with respect to constant L-shells ranges from 0 to 0.5 L per hour LT [Hoch and Smith, 1971].
- c) SAR arcs have been most frequently observed between $L = 2.8$ and $L = 3.4$ with a maximum at $L = 3$ (see Figure 2). The absence of observations beyond $L = 4.5$ may result from absence of routinely operated stations at higher latitudes.
- d) When SAR arcs are mapped along magnetic field lines into the equatorial plane as illustrated in figure 3, the locus of the successive observations typically resembles the plasmapause boundary, with a smaller radial distance on the dawnside than on the dusk side [Carpenter, 1971; Hoch and Smith, 1971]. Glass *et al.* [1970] have shown that this characteristic tilt or asymmetry is associated with the apparent equatorward drift of SAR arcs with a velocity of 50-100 km/hour (i.e. $\sim 0.1 - 0.2$ L per hour LT) reported by Roach and Roach [1963].
- e) From direct correlated observations it appears that the SAR arc is either just inside or just outside the plasmapause, but that for the whole duration of an observation the position of the arc remains in some definite place with respect to the plasmapause [Carpenter, 1971; Chappell *et al.*, 1971; LaValle and Elliot, 1972; Nagy *et al.*, 1972].
- f) The SAR arc is definitely associated with the mid-latitude electron trough. A depression of a factor of 4 in the electron density has been measured above SAR arcs. Electron temperatures of 6000° to 9000° K were also observed at an altitude of 1200 km along the magnetic field line of the arc. [Norton and Findlay, 1969; Roble *et al.*, 1971].

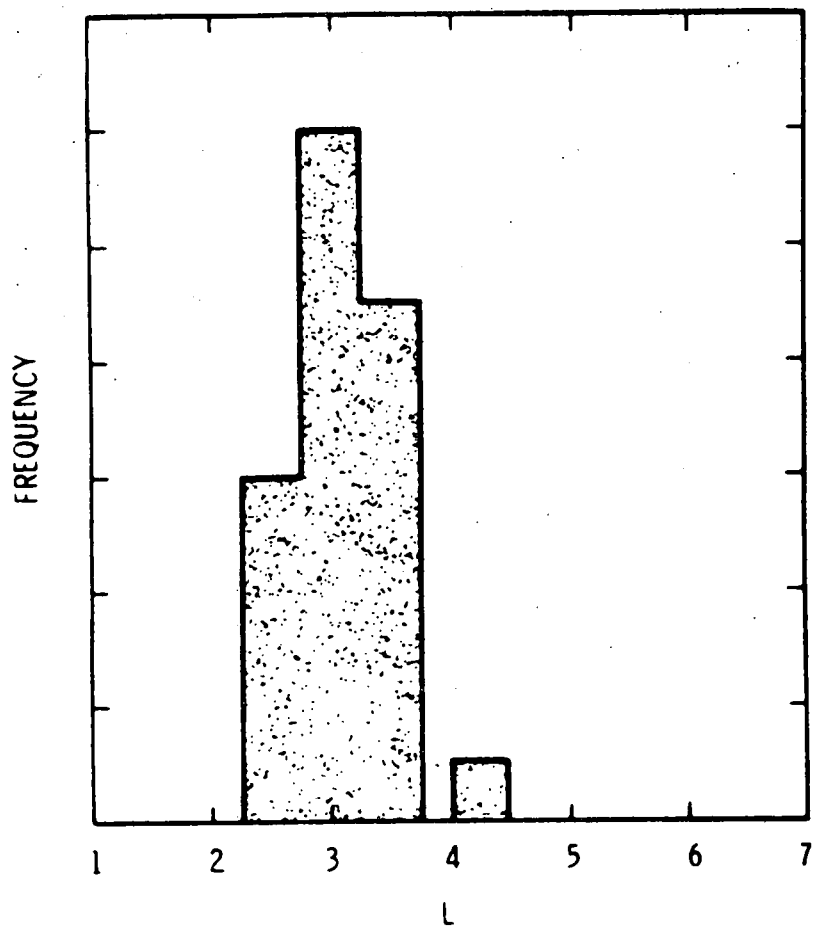


Fig. 2.- SAR arc frequency distribution as a function of L from 1967 to 1973 [Hoch, 1973].

- g) Polar orbiting satellite observations of SAR arcs show conjugate SAR arcs in both hemispheres near magnetically conjugate areas [Reed and Blamont, 1968].
- h) In figure 3 successive fronts corresponding to 15 minutes intervals are illustrated. In figures 3a and 3b there appears to be a corotating bulge which probably corresponds to a longitudinal irregularity in the plasmopause surface as reported by Park and Carpenter [1970] and Bullough and Sagredo [1970].

2.5. Frequency

- a) SAR arcs are often considered rare events compared to polar auroras. However, during the recent solar maximum, a SAR arc of 50 Rayleighs or greater intensity was detected approximately one out of every ten clear nights that observations were made at Battelle Observatory ($L = 2.9$). Frequency of occurrence depends strongly on the level of solar activity; a higher frequency is obtained at solar maximum, i.e. precisely when Barbier [1958] discovered SAR arcs in France.
- b) The subvisual emission of SAR arc is observed during night time. However it is possible that SAR arcs also occur during the day but that sunlight prevents detection of the faint radiation [Hoch, 1973].
- c) It is peculiar that SAR arcs are most frequently observed during equinoxes, but almost never during northern summer nights [Hoch 1973].
- d) The occurrence of SAR arcs is directly related to the occurrence of geomagnetic storms : no SAR arc has ever been observed when the magnetosphere was not disturbed. The intensity of SAR arcs is positively correlated with the strength of the associated magnetic disturbance measured by D_{st} [Rees and Akasofu, 1963].

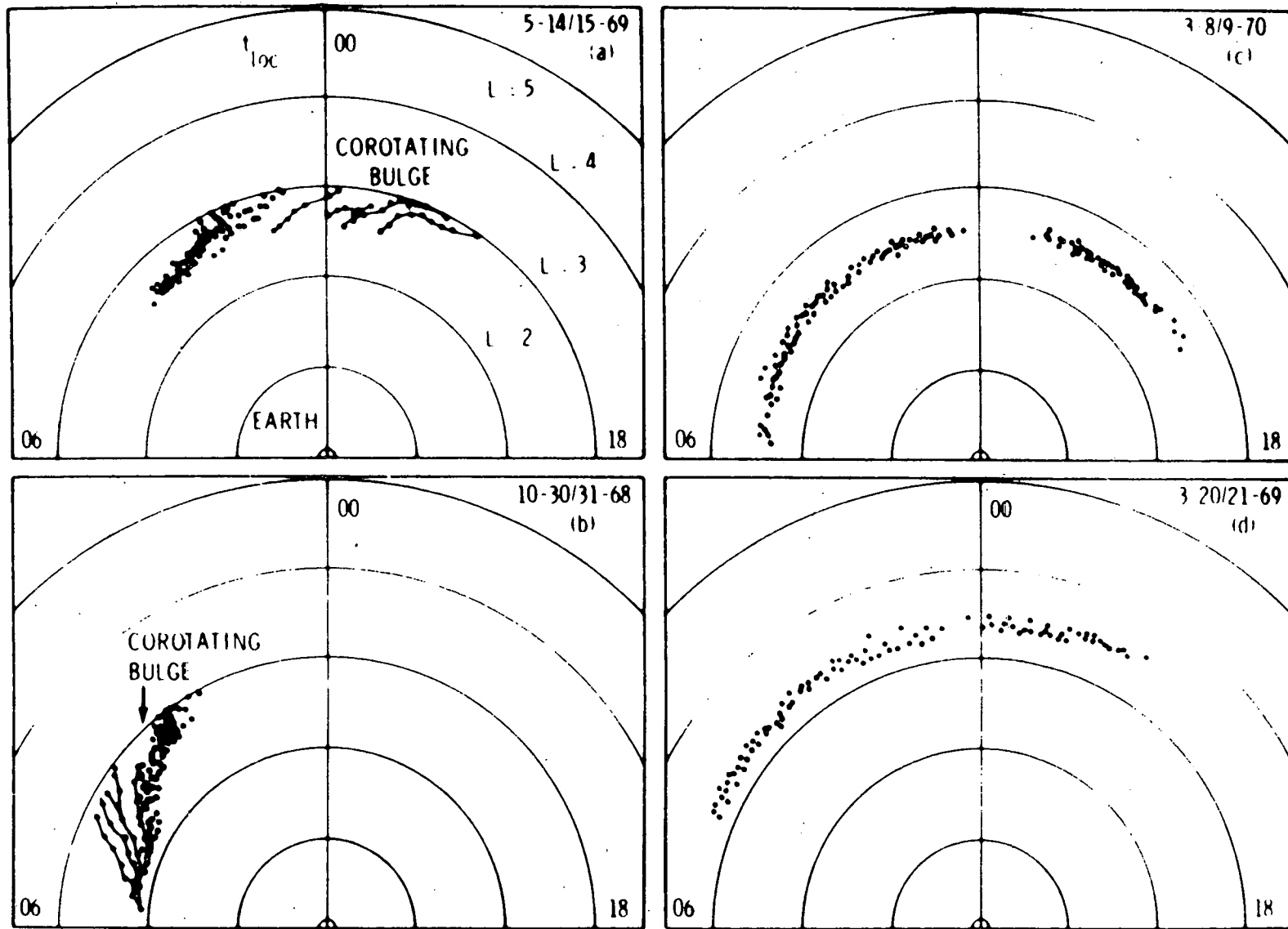


Fig. 3.- SAR arc positions mapped along field lines into the equatorial plane of the magnetosphere. Occasionally, sets of points from successive instantaneous 'snapshots' of the SAR arc define a moving distortion, as shown in *a* and *b*. The successive fronts correspond to 15 minutes time intervals and indicate the presence of a corotating bulge in the plasmasphere. Often the surface of the plasmasphere is relatively smooth, as shown in *c* and *d*. The break in the data near midnight in *c* and the fact that the other maps do not span the entire dark side are due to meteorological conditions that prevented measurements [Hoch, 1973].

- e) On every occasion a SAR arc was observed, a polar aurora has also been seen at the same time, but at a more poleward latitude [Hoch and Clark, 1970]. Hydrogen arcs occur at about 1 to 2 L values polewards of SAR arcs. On every occasion that an H-arc is detected, a SAR arc has been detected simultaneously if SAR arc observations were being made when the H arc occurred [Kleckner and Hoch, 1973].

3. THE THEORIES

3.1. Source

Cole [1965] suggested that the energy stored in trapped Ring Current particles is the source of SAR arc emissions. He showed that the rate of decay of kinetic energy associated with a $100 \gamma D_{st}$ geomagnetic storm is of the order of 3×10^{17} ergs sec^{-1} (assuming a characteristic recovery period of 10^5 seconds). This energy loss of Ring Current particles is more than 50 times larger than the energy radiated as red light by a SAR arc of 10 kR. The major part of this R.C. energy is dissipated into the midlatitude atmosphere by increasing the temperature of the ionized and neutral constituents.

Although nobody disputes the fact that the SAR arc energy comes from the Ring Current, there remains however a controversy about the physical mechanism by which this energy is transferred from the 10 keV protons to the 1 eV ambient ionospheric electrons in the region of SAR arc formation.

3.2. Coulomb collisions

Cole [1965, 1970] suggested that the R.C. protons are degraded in energy by Coulomb collisions with "background" magnetospheric "thermalized" plasma of a temperature of about $10,000^\circ \text{K}$. Heat conduction transports this energy downward to the ionosphere and maintains there a sufficiently high electron temperature ($> 3200^\circ \text{K}$) to excite the Oxygen

atoms in the 1D state by collisions. At altitudes above 300 km the collision time between particles becomes sufficiently large so that a significant fraction of excited Oxygen atoms are deactivated by radiative transition and emission of radiation at λ 6300 can occur.

Using a self-consistent neutral atmosphere model allowing for changes in the neutral composition and temperature during a geomagnetic storm, Chandra *et al.* [1972] have shown that the thermal conduction mechanism is able to produce sufficiently bright arcs [Roble *et al.*, 1971].

3.3. Wave-Particle interactions

Cornwall *et al.* [1970, 1971] argued however that Coulomb interactions are not sufficient to excite SAR arcs of 1 kR intensity or more. They suggested that the plasmasphere expands into the Ring Current region during the main phase of a geomagnetic storm. When the cold plasma density reaches about 100 cm^{-3} the R.C. protons of 20 keV become unstable and intense ion-cyclotron wave turbulence is generated in a narrow region just inside the plasmapause. According to their calculations half of the R.C. energy is then dissipated into transverse hydromagnetic waves, which in turn is absorbed through Landau damping with the colder electrons of the plasmasphere. The thermal heat flux to the ionosphere due to Landau absorption of the wave energy should be sufficient to drive SAR arcs of the observed intensities. The other half of R.C. particles, are supposed to be precipitated and to lose their energy by Coulomb collisions with the ambient electrons.

At least three remarks have been made with respect to this theory : (i) during the main phase of a geomagnetic storm the plasmasphere seems not to expand rapidly as required by Cornwall *et al.*'s mechanism to explain the rapid decay of R.C. particles; the region beyond the plasmapause is progressively filled up with plasma while the plasmapause boundary remains at fixed L values [Pudovkin, 1974]. This is also supported by the absence of poleward motion of SAR arcs [Hoch, 1973]. (ii) Recently Prölss [1973] has recalculated the effect of charge-exchange collisions between hot R.C. protons and neutral Hydrogen atoms

of the geocorona. He finds that charge exchange is a very efficient process in removing R.C. energy from L shells up to $L = 4$, and he suggested that this may be the dominant loss mechanism in this region. (iii) No evidence of the proton precipitation in the SAR arc region, which should give rise to some hydrogen Balmer emission, is observed [Hoch, 1973].

Hoch [1970] and Hasegawa [1971] showed that longitudinal waves also become unstable when the density gradient at the plasmopause is sufficiently steep to trigger drift-wave instability. These longitudinal waves may also contribute to the heating of the electrons and this mechanism may be quite appropriate for the formation of SAR arcs.

3.4. Particle precipitation

Although Chandra *et al.* [1971] reported a SAR arc observation with no significant measured enhancement of energetic electron influx, it is not yet possible to rule out the contribution of direct particle precipitation to the formation of SAR arcs [Dalgarno, 1964]. Such a superimposed precipitation seems indeed to be required to explain the trace emissions $\lambda\lambda$ 5577, 5200, 4278 at the lower altitudes [Hoch *et al.*, 1971].

4. CONCLUSIONS

From this brief report it can be concluded that the theory of SAR arc formation is not yet clearly settled, and that an increased number of routine stations with highly sensitive equipment would help a great deal to understand more about the plasmopause and Ring Current regions.

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