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Stable auroral red arcs and their importance for the physics of the Plasmapause region*

by

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RESUME. – *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 plasmapause et le courant annulaire est décrite. On discute également les différentes théories proposées pour la formation des arcs 'SAR'.*

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 occurrence and the position of these subvisual line emissions are reported. Their close connection with the Plasmapause and Ring Current regions is described. The different theories proposed for the formation of SAR arcs are also reviewed and briefly discussed.*

1. Introduction

The purpose of this paper is to emphasize the importance of Stable Auroral Red arcs (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.

Recent reviews on SAR arcs have been published by Nagy *et al.* [1970], Hoch [1973], Roble and Rees [1974] and Pudovkin [1974].

2. Observations

2.1. Spectrum

a) The radiation of SAR arcs is predominantly a red line emission at λ 6 300 and λ 6 364, corresponding to the transition of atomic Oxygen from the excited ^1D state to the ^3P ground level [Barbier,

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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 5 577 ($^1S - {}^3P$ of OI) are also observed with an intensity less than 2 % of the principal λ 6 300 radiation [Barbier, 1958, 1960, Hoch *et al.*, 1971].

c) The N_2^+ emissions, for example λ 4 278 and the neutral atomic nitrogen line emission λ 5 200 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 6 300 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 over a wide range between 10 kR and 50 Rayleighs [Hoch, 1973]. Due to limitations of instrumental sensivity, 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.

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 with respect to a certain L shell, so that the westward side is at a higher L value 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].

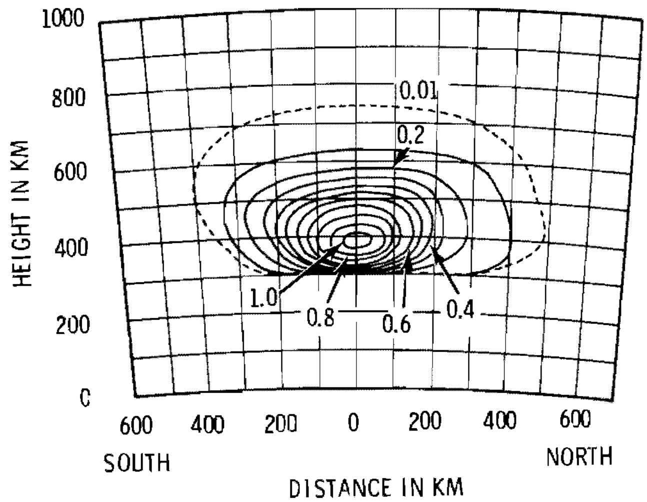

Fig. 1
Spatial distribution of intensity for an average SAR arc [Tohmatsu and Roach, 1962].

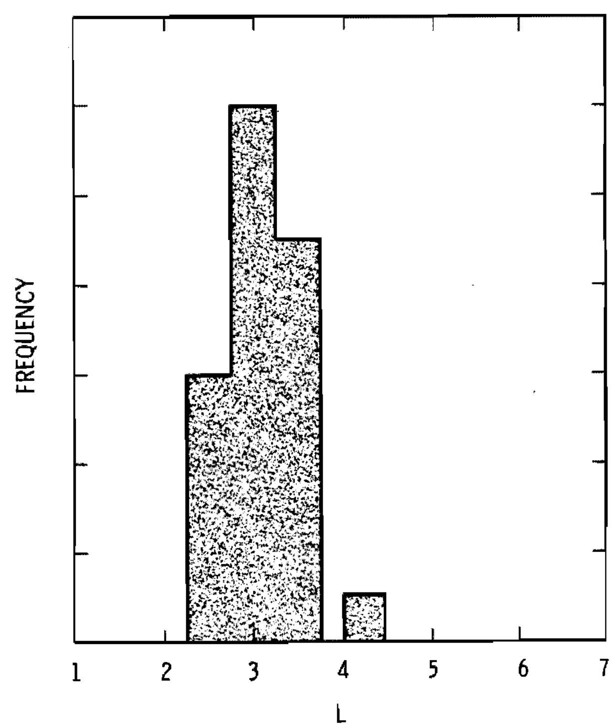

Fig. 2
SAR arc frequency distribution as a function of L from 1967 to 1973 [Hoch, 1973].

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 the 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 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. ~ 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 6 000° to 9 000° K were also observed at an altitude of 1 200 km along the magnetic field line of the arc [Norton and Findlay, 1969 ; Roble *et al.*, 1971].

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 plasmapause 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 the 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].

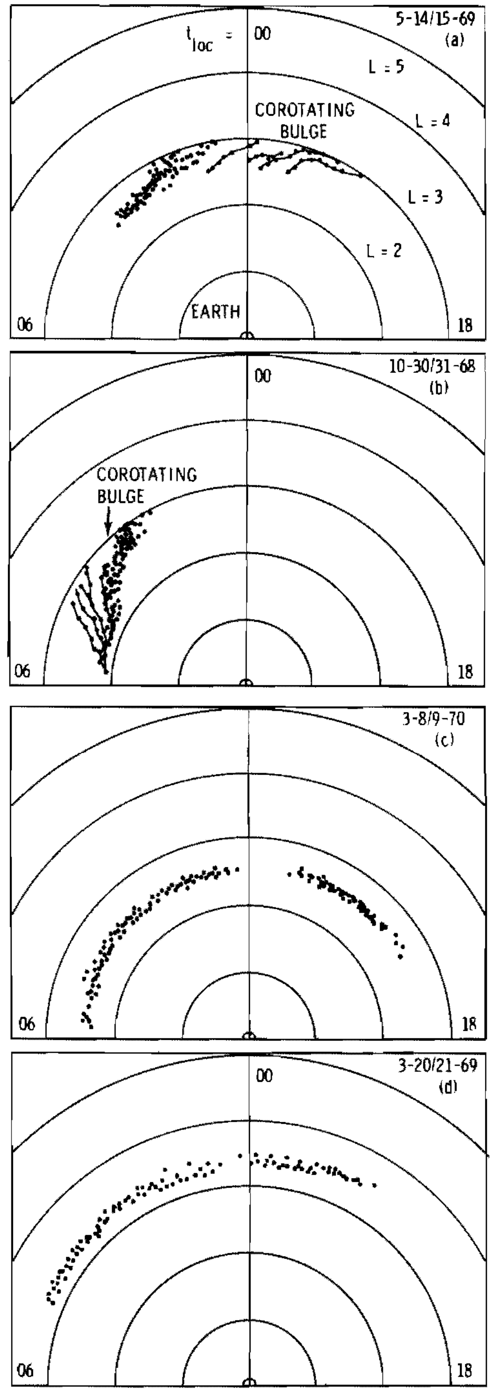

Fig. 3

SAR arc positions mapped along field lines into the equatorial plane of the magnetosphere. Occasionaly, 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].

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 occurence 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].

e) On every occasion that a SAR arc was observed, a polar aurora was also 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 γ 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 concerning the physical mechanism by which this energy is transfered 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 Ring Current protons are degraded in energy by Coulomb collisions with "background" magnetospheric "thermalized" plasma of a temperature of about 10 000° K. Heat conduction transports this energy downward to the ionosphere and maintains there a sufficiently high electron temperature ($> 3\,200°$ K) to excite the Oxygen atoms into 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 transitions and emission of radiation at λ 6 300 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}, 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 Ring Current 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 Ring Current particles, energy is supposed to be given to the precipitated particles which 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 does not seem to expand sufficiently rapidly to explain the rapid decay of Ring Current particles ; the region beyond the plasmapause is progressively filled up with plasma while the plasmapause boundary remains at fixed L values [Pudovkin, 1974]. This result 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 Ring Current protons and neutral Hydrogen atoms of the geocorona. He finds that charge exchange is a very efficient process in removing Ring Current 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 plasmapause is sufficiently steep to trigger the 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 has not yet been 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 λλ 5 577, 5 200, 4 278 at the lower altitudes [Hoch *et al.*, 1971].

4. Conclusions

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 plasmapause and Ring Current regions.

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