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Effect of South Pacific Magnetic Anomaly (SPMA) on VLF Emissions Observed at Low Latitude

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Abstract

VLF emissions recorded at Ariel satellite show high spectral density along with occurrence rate in the longitude range of 100-140 ⁰ east. We consider this region which is known as South Pacific Magnetic Anomaly (SPMA) as the source of cyclotron instability to produce high occurrence rate with spectral density. Various phenomenons have been considered which effect the whistler mode VLF amplification. Various kinds of observations as well as theoretical work done in the field support our result.

Keywords: Cyclotron instability mechanism, VLF emissions, Electron precipitation.

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Introduction

There are two kinds of anomalies. The first one is called SAMA (South Atlantic

Magnetic Anomaly) and the other one is known as SPMA (South Pacific Magnetic Anomaly). Both anomalies have different longitude and latitude ranges and effect the wave particle interactions occurring in ionosphere and magnetosphere. Much work has already been done on SAMA. In this paper we study effect of SPMA on whistler mode VLF emissions generation. Singh et al[1] made a detailed study of Ariel 4 satellite data on low latitude VLF emissions[2,3,4]. The analysis of these data point out that:

1. The low latitude VLF emissions are propagating in whistler (prolongitudinal/non-ducted) mode.
2. These emissions are of impulsive nature and find their origin in lighting discharges.
3. 3.2 KHz emissions have a mean spectral intensity of 4.8 x 10^{-15} Wm^{-2} Hz^{-1} (i.e. 40 dB above free space equivalent 4.8 x 10^{-19} Wm^{-2} Hz^{-1}).
4. The peak to mean intensity ratio for 3.2 KHz emissions vary between 5 and 50 dB having a maximum occurrence number of about 166 for K_p value between 0 and 2, and 81 for K_p values between 3_- and 5_+.
5. The mean to minimum intensity ratio varies between 1 and 30 dB having maximum occurrence number of 90 for K_p values ranging between 0 and 2_+, and 40 for $K_p = 3_- - 5_+$.
6. 3.2 KHz emissions have high occurrence number and high intensity at magnetic local time (MLT) = 16-20 hrs.
7. During MLT = 16-20 hrs, for K_p values of $0\text{-}2_+$ north-zone emissions have intensity of the order of 50-60 dB. This intensity is not observed in south-zone. Number of such highly intense emissions in the north-zone is (approximately) 10% of the total events. The latitude range of observations in this case in both zones is 10° -30°.
8. During MLT = 16-20 hrs, for $K_p = 3_- - 5_+$ such intense emissions are not observed in the north-zone but actually they are less intense than those in the south-zone. Singh et al[1] have explained these intensity peaks (points 7 and 8) in terms of cyclotron wave amplification.
9. Highest occurrence of VLF emissions is observed at 100-140° E longitude range for both north and south zone. Occurrence rate and intensity observed for $Kp = 3_- - 5_+$ are found to be lower than observations for $K_p = 0\text{-}2_+$. Intensities at these K_p values in this longitude range are ≥ 60 dB.

Hayakawa[5] has shown that these VLF emissions have their source in lightning discharges. Singh et al[1]observed that intense peaks in these emissions recorded in north-zone are due to wave particle interaction in the equatorial region. These waves (~ 10%) are actually generated in south-zone and propagate along the geomagnetic field lines to be observed in north-zone. The energetic electrons coming from northern zone give away their energy to the interacting wave to amplify it. This amplified wave is observed in N-zone and precipitated electrons are observed in S-zone. The mode of interaction considered by them was cyclotron resonance.

In this paper authors explain intensity peaks and high occurrence rate of 3.2 KHz VLF emissions observed in the longitude interval of 100-140°E in terms of effect of South Pacific Magnetic Anomaly (SPMA).

South Pacific Magnetic Anomaly (SPMA)

It is well known that whereas center of SAMA has minimum geomagnetic induction 'B', SPMA center has highest magnetic field. The SAMA zone lies between 0-50°S latitudes and 30°E-120°W longitudes having its center[6] at 45°W. This center of SAMA has shifted a few degrees to the west in last 20 years due to secular variation of the fields[1,7]. Although, the center of SAMA is located at L = 1.3, its effect has been observed from L = 1.1 to L = 1.4 (ref.7). It is well known that the asymmetry of the 'B' values at end points of a field line in northern and southern hemispheres increase the wave particle interaction, which may lead to increased particle precipitation and wave intensification.

The center of SPMA (with maximum 'B' value) is located at 140°E longitude and 60°S latitude. The asymmetry in 'B' values around SPMA center is shown in Table 1. this asymmetry is responsible for enhanced wave-particle interaction, energetic particle precipitation and wave intensification. Pinto and Gonzalez[6] depicted that particle precipitation is more around SAMA region in southern hemisphere than in northern hemisphere. The same is true for SPMA region, though in this case electron precipitation is not so strong but moderate[7].

Method of Calculation and Ionsopheric Model

To study the amplification of low latitude VLF emissions, the VLF waves propagating (approximately) along geomagnetic field lines L = 1.1, 1.3 and 1.5 which correspond to geomagnetic latitude of 20°, 29° and 35° respectively are considered. Following Kennel and Petschek[8] the growth (γ) is computed from the expression

$$\gamma = \pi.\bar{A}.\eta.\omega_H \tag{1}$$

where ω_H is electron cyclotron frequency, $\eta = \frac{N_e}{N_o}$, the fractional concentration of energetic electrons. The pitch angle anisotropy A is expressed as

$$A = \frac{1}{2\ln(1/\sin\alpha_O)} \tag{2}$$

α_o is loss cone pitch angle. The gain in wave intensity during cyclotron resonant interaction in the equatorial region is expressed as[9]

$$G = 2\int_{\substack{unstable\\region}} \gamma dt = \frac{2\gamma.L.R_o}{Vg} \tag{3}$$

R_o is earth radius (6370 km) and V_g is group velocity which is expressed as

$$v_g = 2c\frac{\omega_H}{\omega_P}\left[\frac{\omega}{\omega_H}\right]^{1/2}\left[1-\frac{\omega}{\omega_H}\right]^{3/2} \tag{4}$$

where ω_p is the electron plasma frequency and ω the wave frequency. The gain in terms of dB is written as[10]

$$\text{Gain (dB)} = 10 \log (e^{G}) \qquad (5)$$

The parallel resonant velocity and energy of interacting energetic electrons are computed using the relations[11]

$$V_{\|} = C\left(1 - y_r^{-2}\right)^{1/2} \qquad (6)$$

and

$$E_{\|} = (y_r - 1)m_o c^2 = (y_r - 1)\, 511\, keV \qquad (7)$$

where

$$y_r^2 - 1 = \left[\frac{\omega_H}{\omega_P}\right]^2 \left[\frac{\omega_H}{\omega}\right] \left[1 + \frac{\omega_H^+}{\omega}\right] \qquad (8)$$

and ω_H^{+} is proton cyclotron frequency ($\equiv \omega_H /1836$). The resonant energies at 1.1 – 1.5 L-shells are found to be >1 MeV. Number densities for energetic electrons in this energy range at L = 1.1-1.5 are taken from figure 1 of Katz[12] (1969).

Familiar diffusive equilibrium (D-E) model of Angerami and Thomas[13] of the ionosphere is employed. This model is represented by an electron density of 1.5×10^5 el/cm^3 with 95% O^+, 4.75% He^+ and 0.25% H^+ at 400 km reference level having a temperature of 1000 K. These electron and ion densities are the observed values from satellites Alouette-1 and Injum-3 (ref.13). Several workers[14,15] have used this D-E ionospheric model for their studies at low latitudes. This model produces electron concentration at L = 1.1, 1.3 and 1.5 to be 20×10^3, 4.61×10^3 and 2.71×10^3 el/cm^3 respectively.

Results and Discussion

The growth rate strongly depends upon velocity-pitch angle distribution function F (E,α). The considered F (E,α) in our case is given below

$$= 0 \quad 0<\alpha< \alpha_o$$

$$= E^{-2} \log \frac{\sin\alpha}{\sin\alpha_o} \quad \alpha_o < \alpha < \pi/2$$

$$F(E,\alpha) = E^{-2} \log \frac{\sin(\pi - \alpha_O)}{\sin(\pi - \alpha)} \quad \pi/2 < \alpha < \pi - \alpha_o$$

$$= 0 \quad \pi - \alpha_o < \alpha < \pi$$

Above shown mirror type configuration has following properties

$$\partial F / \partial \alpha \geq 0 \quad 0 < \alpha < \pi/2$$
$$\partial F / \partial \alpha \leq 0 \quad \pi/2 < \alpha < \pi$$

Here E is particle energy, α is particle's pitch angle and α_o is half loss cone pitch angle. Kennel [16] has shown that such a hard distribution function gives wavegrowth for whistler mode waves from θ (wavenormal angle) 0° to 40° i.e., unstable cone of wave normal angles has large size and Landau damping remains almost ineffective in this range.

The propagating wave interacts with energetic counter streaming electron beams. During interaction electron loses parts of its energy to the wave and its pitch angle is reduced. After one or two complete bounces the interacting electrons with reduced pitch angle ($\alpha < \alpha_o$) lying in the loss cone are precipitated. The electrons with pitch angle $\alpha > \alpha_o$ are always responsible for wave amplification. Thus, the cyclotron instability is responsible for VLF wave intensification in 100-140°E longitude. The condition for cyclotron resonance between energetic particles and interacting wave is given by

$$K_{\|} V_{\|} = m\omega_H + \omega \tag{9}$$

where $K_{\|}$ and $V_{\|}$ are components of the wave propagation vector and resonant particle velocity vector parallel to the ambient fields respectively. m is an integer (0, ± 1, ± 2,…). The whistler mode waves considered by us are right hand circularly polarized waves and these can be amplified by negative harmonics only of Thorne and Moses[17].Here we consider only normal cyclotron resonance (m = -1) between whistler mode waves and energetic electrons.

The equatorial half loss cone angle (α_o) at given L (the McIlwain parameter) is computed from following formula [18].

$$\sin^2 \alpha_o = \frac{Em^3}{L^2\sqrt{4L^2 - 3Em.L}}$$

where $Em = (R_o+H_m)/R_o$

H_m is mirror height and varies from 100-140 Km as it is base of ionosphere. The variation of H_m from 100 to 140 km brings no significant change to affect the results[19,20].

Equatorial loss cone pitch angle (α_o) at L = 1.1, 1.3 and 1.5 has values 57.4°, 37° and 28° respectively, at which we find high occurrence and high intensity of low latitude VLF emissions. The above α_o values are computed for 'no anomaly' region. For region of SPMA, these α_o values are found to be ≈ 55°, 36° and 27° at corresponding L values for $H_m \approx 0$ km. For $H_m < 0$ km , we get still (but not so significant) lesser values[21]. We now calculate wave growth (dB) for VLF waves in the longitude range of 100-140°E. For this purpose the energetic electron concentration is computed from observed electron fluxes at the equatorial heights L = 1.1, 1.3 and 1.5. Figure 1 of Katz[12] gives electron fluxes ($E_{\|}$>1MeV) to be 4.0×10^6, 5.0×10^6 , 4.0 ×

10^6 el/cm^2.s.ster at these L shells respectively. Dividing these values with resonant velocities one can get easily the concentration in el/cm^3. N_e values at these altitudes are found to be 16.87× 10^{-4} , 21.12× 10^{-4} and 17.07× 10^{-4} el/cm^3. The G values at corresponding L shells are computed to be 1.0838 - 1.7486 producing the gain to be 7.6dB (L=1.1), 7.2dB(L=1.3)and4.7dB (L=1.5).These gain are just because of SPMA for H_m= 0Km.

Singh et al[1] have computed wave gains due to cyclotron instability for low latitude Ariel 4 satellite VLF emissions under ‘ no anomaly ’ condition. In that case temporal wave growth (γ) values were found to be 3.1869, 3.6548, 2.128 S^{-1} which produced power gain of 9.0 dB, 7.6 dB and 4.9 dB at L = 1.1, 1.3 and1.5 respectively. Table 2 gives power gain and other parameters used in the study for anomaly effects. It is clear from Table-2 that a VLF wave can have amplification of ≈ 23 dB at L = 1.1 in the longitude range of 100-140°E above average values. This clearly explains why the VLF emissions in the longitude range 100-140°E have intensity ≥60dB.

The threshold spectral intensity for Ariel satellite recording was 4.8 × 10^{-19} W m^{-2} Hz^{-1} and waves with intensity below it could not be observed. Since in the SPMA region, a wave can be amplified to a minimum of (4.7+4.6 =) 9.3dB, a large number of VLF emissions could be recorded in the SPMA region which were not observable outside the anomaly regions. Other factors enhancing the occurrence in SPMA region have been explained by Singh and Singh [7].

Figure -1 show variation of power gain with L values for combined conditions in the ionosphere. It is evident from this figure and Table- 2 that first intensity peak is occurring at L = 1.1 P$_{into}$ and G$_{onzalez}$ [6] have shown that for VLF emissions observed in the SAMA/SPMA regions first intensity peak is at L = 1.1 and second L = 1.4 which is consistent with our results. At L ≤ 1.7 we get either no amplification for VLF emissions or very low amplification and at L = 2 there is no amplification. Similar results were reported by Pinto and Gonzalez [6].

The Landau resonance velocity for 3.2 KHz whistler waves in our case is much lower than the cyclotron resonance velocity. Under any realistic velocity distribution function the density of Landau resonant (m=0) electrons should be much higher which may cause wave damping. The damping due to Landau resonance can be computed from following expression given by Kennel and Wong [22],

$$\gamma = -\omega \frac{E_L}{E_M} . \theta^2 \qquad (10)$$

Here E_L is resonant energy of Landau electrons and E_M is magnetic energy per unit particle. Equation (10) can be written as

$$\gamma = -\frac{\omega^2}{\omega_H} \theta^2 \qquad (11)$$

Considering θ = 40° (farthest possibility), we find that equation (11) yields damping rates of 0.019 S^{-1} at L = 1.5 and lesser values at L = 1.1, 1.3. it is clear that the Landau resonant electrons are unable to damp 3.2 KHz whistler mode waves.

Here we assumed high energy electron beam and now assume high energy ions. One may also assume high energy ions with velocity larger than the Alfven velocity. In this case anomalous cyclotrons resonant ions (protons etc.) may cause significant damping (m=+ve). This aspect, too, has been tested here. We compute damping of 3.2 KHz waves by m = +1 mode protons using following expression[17].

$$\gamma(\max) = -\frac{\pi}{2}\Omega_{P^+}\left(\Omega_{P^+}/\omega\right)\frac{\left(1+\omega/\Omega_P\right)^2}{\left(1+\omega/2\Omega_P\right)}\eta_P . A^+ \tag{12}$$

were Ω_p is angular gyrofrequency of protons. Since number of cold protons is less than the number of cold electrons and energetic protons may have density equal to that of energetic electrons, the fractional concentration of energetic protons (n_p) is taken 10 times of electrons fractional concentration. The anisotropy (A^+) for protons is taken similar to that of electrons. These values produce damping rates of 0.016, 0.020 and 0.012 S^{-1} at L = 1.1, 1.3 and 1.5 respectively. In comparison to wave growth by m = -1 electrons, damping by m = +1 protons is negligible. It is also clear from equation (12) that other heavy ions, too, are enable to damp the whistler waves. Moreover, as shown by Thorne and Moses[17], other higher harmonics (whether –ve or +ve) will have no significant contribution towards wave growth/damping.

We have assumed that whistler waves are amplified through the cyclotron resonance instability. One may question what is the physical justification for this assumption? It is to be pointed out here that Tsurutani et al[10] have successfully utilized cyclotron resonance upto L = 1.1 to interpret observation of ELF waves at low L-Shells. Using cyclotron resonance process

Imhof et al[23]explained observed multiple narrow energy peaks in precipitated electron spectra in the inner radiation belt. These measurements were performed from the low altitude polar orbiting satellite P78-1. Jain and Singh[24] adopted cyclotron mechanism to explain low latitude ELF emissions. Jain and Singh[24] have shown that cyclotron instability is the generation process of low latitude ELF emissions. Singh et al[25]explained the observation of discrete chorus emissions recorded at low latitude station Bichpuri (L = 1.1) on the basis of cyclotrons resonance mechanism. Hayakawa[26], on the basis of cyclotron mechanism interpreted whistler triggered VLF emissions observed at low latitude ground station of Moshiri (Geomag. Lat. 34.3°N). These physical justification clearly support our assumption of cyclotron instability as possible amplifier for 3.2 KHz waves at L = 1.1-1.5.

It has been shown that for considered mirror type (or loss cone) distribution function, unstable cone is of 40° wave normal angle. But if wave normal angle is 40° at the equator or in the interaction region than the final wave normal angle at 120 km in the receiving hemisphere will be quite large. In this case final wave normal angle will not lie in the transmission cone which is narrow at low latitude. Thus there will be no observation of whistlers/VLF emissions at low latitudes. Hence to receive VLF emission at low latitudes, the wave normal angle at the interaction region should be lower than 40°. Singh et al[14], Singh and Singh [15] after doing ray tracing computation have shown that the VLF emissions of 3-5 KHz have wave normal angle of 30° or below at an altitude of 1000 km (also see Cerisier[27,28]) and in this case wavenormal angles at the equator should be of10-15^0 or below. Since at low L-shells, electron cyclotron frequency ω_H is quite high ω. ω_H cosθ ≈ ω. ω_H. Thus at low latitudes, propagation is pro-longitudinal[29] which for θ= 10-15° can be approximated to field-aligned propagation for the purpose of dispersion computations.

The cyclotron instability is definitely not very effective at low L shells so far amplification values (in dB) are concerned. At L = 4 cyclotron instability can amplify a wave by a power gain of 40 dB (Helliwell et al [30]) or above whereas at low L shells we observe lesser power gain. Though particle precipitation at low L shells may be enhanced by atmospheric/coulomb scattering (Walt [31], Roederer et al [32]) but in this case energy exchange takes place between energetic electrons and neutral/charged ions. Hence, atmospheric/coulomb scattering has no role in wave amplification. In our case electron ,precipitation occurs in southern zone where B is high i.e. H_m is low (H_m <100 km). Roederer et al [32] have shown that coulomb scattering/atmospheric scattering plays no role, though it has longitudinal dependence, in precipitation of energetic electrons with H_m < 0 km. Because of this, and many other parameters [6] we do not get enhanced electron precipitation (EEP) in SPMA region as is observed in SAMA region.

In our case we get intense waves at or around L = 1.1(figure 1). Tsurutani et al [10] too, reported intense waves at L = 1.1 and less intense waves at L ≥1.7. Since particle precipitation and wave amplification are associated phenomena, we should get significant precipitation at/around L = 1.1. L = 1.1 corresponds to the lower edge of inner radiation belt where electron precipitation has been found always larger than that at the other L (≥1.3) shells [23, 24, 33-36].

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Table 1: Magnetic fields intensity at the earth surface.

Longitude (Degree East)	Magnetic fields intensity (in Gauss)							
	Latitude (degree)							
	20		25		30		35	
	North	South	North	South	North	South	North	South
100	44	51	48	53	50	56	51	58
110	44	52	47	54	50	57	52	59
120	42	52	46	55	48	58	51	60
130	40	52	44	54	47	58	48	60
140	38	51	41	54	44	57	46	59

Table 2: Various parameters used in the study.

L-value	No Anomaly		Anomaly				Total Gain (dB)
	H_m>0km		H_m=0km		H_m<0km		
	α_o (degree)	Gain (dB)	α_o (degree)	Gain (dB)	α_o (degree)	Gain (dB)	
1.1	57.4	9.0	54.7	7.6	52.2	6.6	23.2
1.3	37.7	7.6	36.3	7.2	35.3	6.6	21.6
1.5	28.0	4.9	27.2	4.7	26.4	4.6	14.2

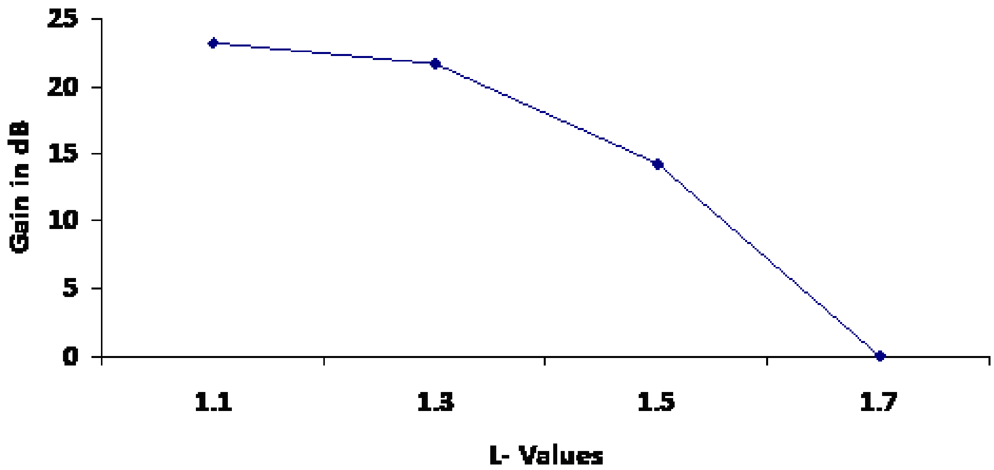

Figure 1: Variation of Power gain with L- Values for various conditions combined [No Anomaly ($H_m > 0$) + Anomaly ($H_m = 0$, $H_m < 0$ Km.)]

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