International Journal of Astrophysics and Space Science
2021; 9(1): 17-20
http://www.sciencepublishinggroup.com/j/ijass
doi: 10.11648/j.ijass.20210901.12
ISSN: 2376-7014 (Print); ISSN: 2376-7022 (Online)

On the Linearized Dynamics of the Neutral Cells at High Latitudes in the Earth's Thermosphere and Exosphere

Vin Bhatnagar

Centre for Research in Earth and Space Science, York University, Toronto, Canada

Email address:
vinbhatnagar1@hotmail.com

To cite this article:
Vin Bhatnagar. On the Linearized Dynamics of the Neutral Cells at High Latitudes in the Earth's Thermosphere and Exosphere. *International Journal of Astrophysics and Space Science*. Vol. 9, No. 1, 2021, pp. 17-20. doi: 10.11648/j.ijass.20210901.12

Received: May 27, 2021; **Accepted**: June 18, 2021; **Published**: June 25, 2021

Abstract: The linearized dynamics of the idealized narrow neutral cells at high latitudes in the absence or presence of auroral energy impulse of the type $q_0\ e^{-at}$ is discussed in the upper atmosphere. The general expression for the oscillation amplitude Δz of the cells is given by $\Delta z = q_0\ [e^{-at} - \cos(\omega t) + a \sin(\omega t)/\omega)]/(a^2 + \omega^2) + \nu_0 \sin(\omega t)/\omega$ Here ν_0 is the cell's initial velocity, ω is its Brunt - Vaisala frequency which varies from about $1.7\text{x}10^{-2}$ at 200 km to $1.3\text{x}10^{-2}$ radians/s at 300 km for an exospheric temperature of 1000 K. The maximum Δz varies from a few km at 200 km for 1000 K to about 25 km at 300 km for 2000 K. For the observed high- and low-density cells, ω is less and high respectively by around 15% than those in the ambient atmosphere at 200 km in the temperature range of 1000-2000K. In absence of ν_0 and q_0, the cells are stable in the thermosphere. The oscillations during disturbed conditions, should eventually cease in the presence of existing nonlinear forces like collision frequencies, emission from atomic constituents, heat conduction and losses, which should be further incorporated to provide a framework for their theoretical interpretation and implications for the high latitudinal thermospheric as well for the ionospheric morphology.

Keywords: Neutral Density Cells, Thermosphere, Exosphere, Ionosphere

1. Introduction

The existence of the neutral cells in the thermosphere was first suspected by De Vries from Logacs experimental campaign in early 70's [7]. Recently these cells in the form of high- and low-density cells were observed by satellite S85-1 during day and night near 60-70 degree magnetic latitude in the lower thermosphere [5]. Such cells have also been confirmed by steady-state Thermospheric – Ionospheric general circulation models, TIGCM [10]. These cells extend upward from about 120 km to 300 km. Some cells may have diameters in the 1 to 2K Km range on a probable time scale of minute to hours. The two cell structure occur only during quiet conditions, while four cell structure occurs during geomagnetic disturbed conditions with two high density cells in the noon-midnight meridian and two low density cells in the dawn-dusk meridian. Single cells normally occur during positive interplanetary magnetic field (IMF). The mechanism and the data analysis of such cells have been further investigated [9, 12, 13]. The enhancements of the high latitudinal density during auroral precipitation have been pointed out [11]. The formation of the cells in the thermosphere depends on the magnetospheric energy input defined by the cross polar cap potential proxies for particle, joule heating, the related transport of the neutral atmosphere, shape of the ionospheric convection patterns and the related ionospheric conductivities. Also, higher the energy input, the higher the cell altitude. Recently the contribution from the altitudinal variations of such cells to the downward transport of the emissions from the atomic oxygen in the high neutral density cell area and its upward transport in the low-density cell area has been discussed [3].

At present, it is not well known as to how these cells with high and low densities once formed respond dynamically to the energy input during aurora and disturbed geospace in their lifetime. Also such studies have implications for the upper atmosphere in the thermosphere/exosphere coupling to high latitudinal ionosphere and its bulk convection [14]. In this work we develop solutions for the linear dynamics for the idealized 'narrow' neutral density cells and neglect the gravity wave effects and other non-linear effects from the known heat losses by emissions from the atomic oxygen and nitric oxide, collisions and the thermal conduction in the thermosphere and the ionosphere.

2. Linear Theoretical Treatment

Let the density and the temperature of the idealized 'narrow' cell formed at the height z_0 be T_c and ρ_c respectively. In this simplified abstraction, the cell temperature is taken constant at its initial value when collision frequencies with ions and electrons, radiation losses and heat conduction are neglected. We also assume that the cells move without much change in the entropy. Let the cells move small height Δz, then the pressure differential is given by

$$\Delta p_c=-g\rho_c\Delta z \quad (1)$$

Now using the First law of thermodynamics for negligible changes in the Entropy, the inside density gradient is known to be given by using equation (1),

$$\Delta\rho_c=\Delta p_c/\gamma RT_c=- g\rho_c.\Delta z/\gamma RT_c \quad (2)$$

where γ is the ratio of specific heats at constant pressure, C_p to at constant volume, C_v (~1.6), R the gas constant and g the acceleration due to gravity. The change in the ambient density outside using Taylor series is given by

$$\Delta\rho=(d\rho/dz).\Delta z \quad (3)$$

Also from the hydrostatic equation in equilibrium, we have

$$d\rho/\rho=-dT/T - \Delta z/H \quad (4)$$

$$d\rho/\rho=-(dT/dz.1/T+1/H)\Delta z \quad (5)$$

where H is the density scale height, T the temperature and ρ the density of the ambient atmosphere at the height of the cell.

Now applying the Newton's second law and the

Archmedian principle, the net buoyant force on the cell per unit volume, can be represented using equations (2, 5) as

$$d^2 \Delta z/dt^2=g (\Delta\rho - \Delta\rho_c)=g (g/\gamma RT_c-1/T. dT/dz - 1/H) \Delta z \quad (6)$$

Now equation (6) can be written as

$$d^2\Delta z/dt^2 + \omega^2 \Delta z=0 \quad (7)$$

This is a second order linear homogeneous differential equation with ω known as the Buoyancy or BVF of the thermosphere at a certain height, such that

$$\omega^2=g (1/T. dT/dz + 1/H - g/\gamma RT_c) \quad (8)$$

It can be seen from equation (8) that in the thermosphere, the BVF, ω depends on the temperature and its height gradient as well on the density scale height, H at its height. It is found out that 1/H is the largest and $g/\gamma RT_c$ is the smallest of the three terms inside. Since ω^2 is positive, the solution of the form $\Delta z=(Ae^{rt} + Be^{-rt})$ where A, B are constants and 't' is the time, can be adopted with

$$r=i\omega \quad (9)$$

If v_0 is the vertical velocity of the cell at height $\Delta z=0$, the solution of the equation (7) can be written as

$$\Delta z=v_0 \sin (\omega t)/\omega \quad (10)$$

Equation (10) represents the free oscillation of the cell, which is an over simplification of the actual case where the auroral energy input/output, q_0 and heat conduction are essentially absent. For a neutral density ρ_c > or < ρ, equation (8) can be written as

$$\omega^2=g [(1/T. dT/dz + 1/H) \rho/\rho_{c-g} / \gamma RT_c] \quad (11)$$

3. Auroral Heating Impulse

At higher latitudes, additional force can be imparted during auroral and geomagnetic events to the cells by energetic electrons from the plasma sheet in the auroral oval particularly during southward interplanetary magnetic field [8] or the closing of the Birkeland currents via electrojets which with enhanced electric fields could produce Joule heating [1] or by soft precipitating electrons (~< 500 ev) directly heating the themosphere and the ionosphere. Let this force be of the type [2]

$$q=q_0 e^{-at} \quad (12)$$

where q_0 is the amplitude and a is the decay coefficient. Typical values of q_0 are 1.6, 3.2 x 10^{-6} ergs/cm^2 s at T_E of 1000 K and 2000 K respectively at exospheric heights. Therefore, equation (7) can be written in a very general case as

$$d^2 \Delta z/dt^2 + \omega^2 \Delta z=q_0 e^{-at} \quad (13)$$

Equation (13) can be solved using Laplace Transforms of the Operation Calculus with boundary conditions at t=0 as

$\Delta z=0$ and the vertical velocity $d\Delta z/dt=v_0$.

The solution of equation (13) is then given by

$$\Delta z=q_0 [e^{-at} - \cos(\omega t) + a \sin(\omega t)/\omega]/(a^2 + \omega^2)+v_0 \sin (\omega t)/\omega. \quad (14)$$

It can be seen from equation (14) that in the absence of the auroral impulse (q_0=0), it reduces to equation (10). In case of a constant energy exchange q_0 (a=0), it reduces to equation (15)

$$\Delta z=q_0 (1-\cos(\omega t))/\omega^2+v_0 \sin(\omega t)/\omega \quad (15)$$

In case of v_0=0, the equation (15) reduces to

$$\Delta z=q_0 (1 - \cos(\omega t))/\omega^2 \quad (16)$$

The vertical drift velocity can be easily calculated from the equation (17) of thermospheric energy budget, on neglecting the heat conduction and the radiation loses

$$v_0=q_0/\rho_c (C_p.dT_c/dh + g) \quad (17)$$

Equations (14) to (17) show that the amplitude of the oscillations increase with the increase in the auroral energy input q_0 and/or v_o.

4. Results and Discussions

On neglecting the non-linear effects on the idealized narrow cells due to the heat transfer by emissions from the atomic oxygen and nitric oxide, viscosity, electron-neutral and ion-neutral drag in the thermosphere and lower F-region respectively, the dynamics of the cells at high latitudes in the presence/absence of auroral energy input is studied. It can be seen in equation (8) that ω^2 is positive so ω is real then the cell will oscillate with BVF. If ω is zero at some height, it will stay where ever it is without oscillating. In extreme case when ω is negative, the cell will be unstable and will not return to its position while oscillating. The effective heights of oscillations for different scenarios are given by equations (10, 14, 15, 16). Assuming a~1 and v_0~0, equation (14) yields negligible amplitudes as expected for stable neutral cells. The values of maximum Δz and ω calculated at 200 km for different values of q_0 at different exospheric T_E [2, 4] from the equation (8, 14) are shown in figure 1. The temperature of the cells T_c has been taken as at their heights of 200 km from the models corresponding to T_E. For a typical T_E of 1000 K, ω is about $1.7x10^{-2}$ at 200 km and $1.3x10^{-2}$ radians/s at 300 km. This means that the cells will oscillate with this amplitude till they are damped by the other non-linear forces as mentioned before. Also the increase in the amplitude of the cells' oscillations with increase in the auroral energy input is shown by equations (14) to (17). According to [6], the density of the enhanced and depleted cells at high latitudes can be higher or lower on average by 30% respectively of the hemispheric average. Taking this into account in equation (11), ω is found less for high density cells and larger for low density cells by around 15% at 200 km in the 1000-2000K range than for the cells in the ambient atmosphere. The largest effect on Δz of the cells is either because of q_0 or v_0, in equation (17), since v_0 is directly proportional to q_0 and inversely proportional to the density ρ_c and dT_c/dh which also decrease with height.

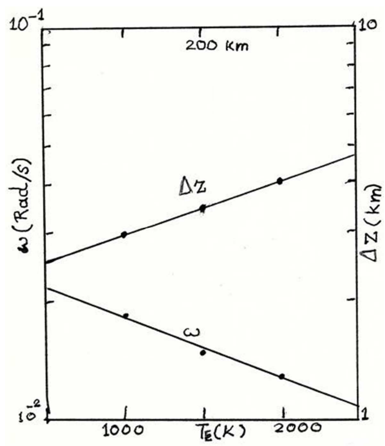

Figure 1. *The variation in the Brunt- Vaisala frequency, ω and maximum amplitude of oscillation, Δz from equation (8) at T_c=T at 200 km with exospheric temperature, T_E.*

Such drifts and oscillations of the neutral cells are of vital importance to neutral and ionospheric dynamics and should be further investigated from the point of view of interpreting high latitudinal data and their coupling to and implications. The influence of nonlinearities on the present results should also be looked into.

5. Conclusions

The dynamics of the idealized narrow neutral cells at high latitudes in the thermosphere and exosphere has been investigated while neglecting the various nonlinear forces like collisions with ions and electrons, the heat conduction and radiation loses by the atmospheric constituents. It is found out that in the absence of any auroral energy source, the Brunt-Vaisala frequency (BVF) at 200 km varies from about $1.7x10^{-2}$ at low solar activity (T_E ~1000 K) to about $1.4x10^{-2}$ radians/s at high solar activity of 2000 K. These agree fairly well with the past value of about 1.1×10^{-2} at 200 km to about $0.4x10^{-1}$ at 300 km [15]. The corresponding variations in maximum Δz is from about 3.0 km at T_E ~ 1000 K increasing to about 4 km at 200 km and 25 km at 300 km for T_E ~2000 K. The BVF for the observed high- and low density cells are found lower and higher respectively by around 15% at 200 km than for the parcel cells at ambient atmospheric density. The increase in the amplitude of the cells' oscillations with increase in the auroral energy input is discussed here. It is suggested that such drifts and oscillations should be further investigated in presence of various nonlinear forces neglected here and their possible implications to high latitudinal neutral atmosphere and also to the ionosphere at thermospheric / exospheric heights.

Acknowledgements

The author thanks Prof. Gordon G. Shepherd for the support.

References

[1] Ahn, B. H, Akasofu, S. I and Kamide, Y, The joule heating production rate and the particle injection rates a function of geomagnetic indices AE and AL, J. Geophys. Res., 88, 6275, 1983.

[2] Bhatnagar, V. P, A. Tan and R. Ramachandaran, The response of the exospheric temperature to the auroral heating impulse during geomagnetic disturbances, J. Atmosph. Solar Terr. Physics, 68, 1237, 2006.

[3] Bhatnagar, V. P, Coupling of the localized wind wall at high latitudes by neutral cells to the lower thermosphere, Int. J. Astrophysics & Space science, 8 (3), 27, 2020

[4] CIRA, Cospar International Reference Atmosphere, North Holland, Amsterdam, 1972.

[5] Crowley, G, J. Schoendorf, R. G. Roble and F. A. Marcos, Satellite observations of neutral density cells in the lower thermosphere at high latitudes, In' The Upper Mesosphere and the Lower Thermosphere: A review of experiment and theory', R. M. Johnson and T. L. Killeen (Eds), AGU Monograph# 87, 339, 1995.

[6] Crowley, G, J. Schoendorf, R, G. Roble and F. A. Marcos, Cellular structures in the high-latitude thermosphere, J. Geophys. Res., 101, 211, 1996.

[7] De Vries, L. L, Analysis and interpretation of density data from the low-G accelerometer calibration systems (Logacs), Space Res., XII, Akademie Verlag, 777, 1972.

[8] Hardy, D, Gussenhoven, M. S and Holeman, E., A statistical model of auroral electron precipitation, J. Geophys. Res., 90, 4229, 1985.

[9] Liu, H, H. Luhr, V. Heinze and W. Kohler, Global distribution of the thermospheric total mass density from CHAMP, J. Geophys. Res., 110, A04301, 2005.

[10] Roble, R. G, E. C. Ridley, A. D. Richmond and R. E. Dickinson, A coupled thermospheric/ionospheric general circulation model, Geophys. Res. Letters, 15, 1325, 1988.

[11] Sadler, F. B, M. Lessard, E. Lund, A. Otto and H. Luhr, Annual precipitation / ion upwelling as a driver of neutral density enhancement in the cusp, J. Atmos. Solar Terr. Phys., 87/88, 82, 2012.

[12] Schoendorf, J, G. Crowley, R. G Roble and F. A. Marcos, Neutral density cells in the high latitude thermosphere—1, Solar maximum cell morphology and data analysis, J. Atmos. Terr. Phys., 58, 1751, 1996.

[13] Schoendorf, J, G. Crowley and R. G Roble, Neutral density cells in the high latitude thermosphere—2, Mechanisms, J. Atmos. Terr. Phys., 58, 1769, 1996.

[14] Smith, P. R, P. L. Dyson, D. P. Monselesan and R. J. Morris,

[15] Ionospheric convection at Casey, a southern Polar Cap station, J. Geophys. Res., 103, 2209, 1998.

[16] Tolstoy, I and P. Pan, Simplified atmospheric models and the properties of long period internal and surface gravity waves, J. Atmos. Sci., 70, 31, 1970.