AGRO PRODUCTIVIDAD

Colegio de Postgraduados

New electrostatic theory for the ascent of sap in tall trees

Aceves-Navarro, E.[1]; Aceves-Navarro, L.A.[2]; Rivera-Hernández, B.[3*]

[1] Fideicomiso de Riesgo Compartido Gerencia Estatal en Campeche, Av. Ruiz Cortines No.112, Edificio Las Torres de Cristal" Torre "A" 8º piso, Barrio de San Román, Campeche, Campeche. C.P. 24040.
[2] Colegio de Postgraduados-Campus Tabasco, Carretera Cárdenas-Huimanguillo, km 3.5, Cárdenas, Tabasco, México. C.P. 86500.
[3] Universidad Popular de la Chontalpa, Carretera Cárdenas-Huimanguillo, km 2.0, R/a Paso y Playa, Cárdenas, Tabasco. C.P. 86555.
* Correspondence: benigno.rivera@upch.mx

ABSTRACT

Objective: to propose a new electrostatic theory for sap ascent in tall trees.
Design/Methodology/Approach: we accomplished a detailed review of the different theories published regarding sap ascent by capillary in trees. The new theory proposed herein is based on some scientific studies of physiologists, biophysicists, and other branches of science, which expose the scientific bases of the water movement in the plant, but who have not proposed an integrated framework.
Results: the proposed theory analyzed prior knowledge, then based on it, a new explanation is proposed for the ascent of sap in trees.
Study Limitations/Implications: no field experiments were carried out to verify the increase in sap ascent in trees with heights greater than 40 m.
Findings/Conclusions: this new theory helps to better explain water loss through transpiration and metabolic processes, since both are closely related to the water content in the mobile solution in conducting vessels.

Keywords: ion hydration shells, ice-like polarized water layer, electrostatic potential, mobile solution column.

Citation: Aceves-Navarro, E., Aceves-Navarro, L.A., &Rivera-Hernández, B. (2024). New electrostatic theory for the ascent of sap in tall trees. *Agro Productividad*. https://doi.org/10.32854/agrop.v17i11.2901

Academic Editor: Jorge Cadena Iñiguez
Associate Editor: Dra. Lucero del Mar Ruiz Posadas
Guest Editor: Daniel Alejandro Cadena Zamudio

Received: May 10, 2024.
Accepted: October 23, 2024.
Published on-line: December XX, 2024.

Agro Productividad, 17(11). November. 2024. pp: 183-191.

INTRODUCTION

An electrostatic theory is proposed to explain the ascent of the sap in tall trees. It was established by considering the existence of ice-like water structure layers present in soils and plants, reported in scientific literature (Ohe *et al.*, 2007; Smolin *et al.*, 2008; Dhopatkar *et al.*, 2016).

The phenomenon is based on a few characteristics of water molecules and their behavior inside soil and plants, as well as the electrostatic fields which they are in contact. When water molecules are in contact with electrostatic force fields existing in soils, ions, or plant tissues, water molecules form a permanent polarized layer with an ice-like structure. This is free of ions and hydrate dissolved substances (Aceves, 1994). This process occurs in

inorganic crystals of clay and in all the hydrophilic organic substances, which are abundant in plant tissues. This ice-like hydration at ordinary temperatures occurs in proteins (Smolin and Daggett 2008) and in practically all cellular surfaces. Bernal (1965) reported that at distances of 10 to 20 Angstrom from the surface of the tissues, water is bonded to them in the form of ice, free of ions.

The presence of permanent ice-like polarized water molecules in membranes pores and the conductive vessels of xylem is fundamental and indispensable in sap ascent from the roots to the leaves of tall trees (Aceves, 1994). It is important to mention that plant life depends on whether they have in their tissues the adsorbed layer of permanent polarized water molecules, with ice-like structure or not, because this layer retains by hydrogen bonds the mobile solution column in the conductive vessels and restore it inside the xylem by capillarity when it is broken due to water scarcity in the soil.

When a plant or part of it loses its polarized water layer, it dies, because it is not possible to restore the mobile water column inside the xylem. In this paper we propose that the ascent of soil solution in tall trees is related with hydration and dehydration processes, as well as with the form how the water molecules are adsorbed inside the soil and plants tissues. This mechanism of change in hydration also produces changes in the water matric potential in each point of soil and plants.

By definition the pure water potential at atmospheric pressure is equal to zero. Therefore, the water potential in a solution is negative, less than zero. The formula for the plant total water potential, with their components is:

$$\Psi_t = \Psi_m + \Psi_e + \Psi_\Pi$$

where: Ψ_t=total water potential; Ψ_m=matric potential; Ψ_e=electrostatic potential and Ψ_Π=osmotic potential.

When plants transpiration stops during the night, and the electrostatic potential is neutralized by hydrogen bonds from the mobile solution column, the value of electrostatic potential becomes zero: $\Psi_e=0$, and the osmotic potential become part of the matric potential. Then without transpiration in equilibrium conditions: $\Psi_t=\Psi_m$ and the whole mobile column is retained against gravity force by hydrogen bonds and electrostatic charges. This mechanism avoids tension forces and problems of cavitation.

In supporting the proposed theory, regarding the osmotic potential Ψ_Π, it is important to consider the following. Ions in soils and inside the plants does not exist in free state; they always have a hydration shell neutralizing their electric charge. Their free energy is less than that of the water molecules contained in the bulk solution, no linked to the ions. They move in soils and plants as a kinetic unit, always from higher to lower hydration shells, or water content. The water shells of the ions are formed by two layers, (Bernal, 1965; Dang *et al.*, 1991; Gouin, 1998; Kropman and Bakker, 2001). The first one, named distortion layer, is directly in contact with the ion; the second is the coordination layer, united with the first layer by hydrogen bonds, it neutralizes electrostatic ions charges, negative or positive (Lyubartsev and Laaksonen, 1996).

The water molecules of the coordination layer are strongly polarized and fixed with the ion. In the distortion layer the water molecules are less polarized and can be exchangeable with other ions shell or bulk water molecules, as well as another electrostatic force fields inside soils and plants; always producing electro neutrality due to the bipolarity of the water molecules. The thickness of these water layers depends of the ion charge density, solution concentration, temperature and pressure. The hydration shells of the ions avoid the each other attraction; when two ions inside the solution are attracted, they form a salt and precipitate. Inside the solution as far as the ions keep their hydration shells, they don't attract each other. This fact is very important because in many theoretical analyses made in different fields of the science, it is supposed that Coulomb's Law applies to measure the attraction force between ions contained in a solution. For example, the double diffuse layer theory; in this instance, is a wrong consideration (Aceves, 2011).

On the other hand, the classic physiology for measuring the osmotic potential considers a true semi permeable membrane, which allows the pass of water molecules but not ions. This kind of membranes does not exist in plants. In plants, the ions transportation process occurring in all their membranes never independently passes solutes and water molecules; they pass together as a kinetic unit, with their hydration shells. Water molecules exist inside the solution uncoordinated with the solutes, also, they pass through the cell membrane, pulled by the electrostatic forces in a mechanism named water drag. The angle (or coefficient) of plant membranes reflection, also called selectivity, depends on the ions hydration cells thickness and their degree of polarization of water molecules. Ions and solutes with minimum hydration shells and water molecules strongly polarized, generally does not penetrate the plant membranes because are repelled by the strongly polarized water molecules, with ice-like structure existing inside the membranes pores. This ion repulsion by cell membranes is more common in plants growing in saline soils. This phenomenon is known as membrane selectivity (Aceves, 2011).

It is very important to point out that the osmosis phenomena have been studied in membranes of isolate cells, submerged in solutions with different types of tonicity, isotonic, hypotonic and hypertonic to observe their behavior. From this observation, it the osmosis phenomenon and ions movement inside the tissues of plants are inferred. When an increment in soil solution concentration occurs, the degree of ions hydration also changes, as well as the dynamics of ions penetration through the membranes. This also changes the water solutes proportion inside and out the plant, and a mechanism occurs inside the cells, known as cell osmotic adjustment, that avoids plasmolysis (Aceves, 2011).

In regard to ions transportation through plant membranes, the concept of osmosis changes when the ions hydration shells are considered. Example: supposing a solution, external to a vegetal membrane, with ions concentration of 2, given by 24 units of solute and 12 of solvent water: $24/12=2$; the internal cell solution concentration equals 8, given by 24 units of solute and 3 of solvent water (Figure 1).

As the classical chemistry establishes, the concentration inside the cell is four times bigger than outside, and to explain how the ions penetrate the membrane, against a concentration gradient, a lot of theories and complicated mechanism have been established. For example, the ion carriers without considering water properties, as very reactive compounds in all the

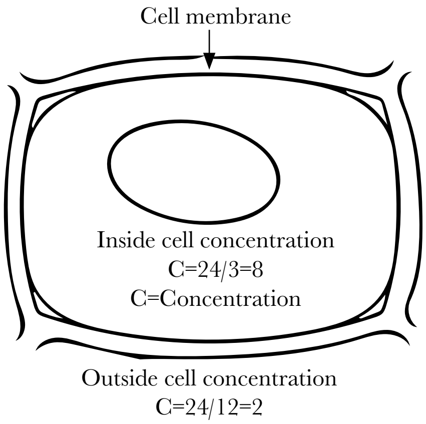

Figure 1. Osmosis as a process of ions hydration shells. Cell model adapted from Azcón-Bieto and Talón (2008).

hydration and dehydration processes including osmosis and solutes transport occurring in soils and inside the plants. The ions keep mobility when they have their hydration shells; as higher is the hydration shell, as bigger the mobility.

Analyzing the example, outside and inside the cell the solute content is the same, 24 units, but there are 4 times more water outside than inside. Considering this situation is reasonable to assume that the ions are four-fold more hydrated outside than inside, and metabolic energy is not needed nor ion carriers for the ions to go inside through the cell membrane channels in a spontaneous process, from higher to lower water content in their hydration shells. Higher concertation inside de cells it does not necessarily mean bigger ions content but less water content. This is another way to see the osmosis phenomenon in the proposed Electrostatic Theory for Sap Ascent in Tall Trees.

Analysis and discussion of the proposed electrostatic theory for sap ascent in tall trees

To explain this theory, it is very important to start by analyzing the mechanism of hydration and dehydration of the ions in the soil and plants solutions (Kropman and Bakker, 2001; Marcus, 2012). Ions in aqueous solution do not exist in a free state; they are surrounded by an envelope or hydration shell with polarized water molecules whose free energy is less than the energy of bulk water molecules (Lyubartsev and Laaksonen, 1996). When an ion with high charge density is in contact with another ion, it can strip it partially or totally from its hydration shell, either in the soil solution or inside the plant (Aceves, 1994; 2011). Water molecules contained in the ion hydration shell can be interchanged with other ions or electric force fields with higher intensity than the ones in contact whit the solution (Aceves, 1994). This is a fundamental principle in dissolved ion mobility and in the explanation of this theory.

The interchange of water molecules between hydration layer ions and dissolved or suspended substances is done constantly. In other words, the ions in the soil solution and inside the plants are subjected to permanent processes of hydration and dehydration (Brownian movements in solutions), and the time of residence of the water molecules in the hydration envelope of an ion, or a dissolved substance is in terms of the charge density or intensity of the electric field; also, concentration, type of ion or substance, temperature, and pressure of the solution.

All ions that lose their minimum hydration shell because of another ion or force field become insoluble and lose their mobility in soils and in plants (Aceves, 1994). Hydration shells of different ions species contained in a solution are different at the same concentration, pressure and temperature. Under the same conditions, some ions get more hydrated than others (the Hofmeister's sequence), in Aceves (1994; 2011). So, in order to explain with greater clarity, the movement and the ascent of ions in solution inside plants, some mechanisms are hypothesized about the way in which water and ions are found inside plant tissues.

Water is found in plant tissues in a similar way as in soils. When water comes into contact with some electric field, a first adsorbed layer of water molecules strongly polarized is formed, with oxygen and hydrogen atoms strongly oriented toward the outside, depending on the electrostatic charge of the tissue surface, and whose structure is similar to that of ice (Aceves, 2011; Dhopatkar *et al.*, 2016). There are not adsorbed ions in this layer, but water molecules are joined, by hydrogen bonds and Van der Waals attraction forces, to the surface of the plant tissues. This cover of polarized water molecules is permanent; its formation starts during seed germination and remains with the approximate same thickness during the entire life period of the plants. This layer of water molecules oriented in an ice-like structure is fundamental for the life of plants and for the passage of organic and inorganic solutes through their plant membranes (Gouin and Kosinski, 1998; Kropman and Bakker, 2001).

The rest of the existing non-strongly polarized ice-like water inside the plant is electrostatic retained and form the mobile water column, associated with mobile solutes, forming their hydration shells or participating in metabolic reactions of hydration and dehydration by water exchange molecules. This mechanism is fundamental for life in all living organisms (Aceves, 1994).

To support the proposed theory, some statements are included:

This entire analysis is based on the classical proposition by Danielli-Davson (1935) as a model of biological membranes, but we modified it to include hydrophilic pores lined by a layer of polarized water molecules and adsorbed in a structure form of ice free of ions (Figure 2).

In order to pass through a biological membrane, an ion must have a suitable hydration shell that allows it to neutralize opposed (of different sign) electrostatic charges which are generated by the adsorbed and polarized water molecules with ice-like structure, within the polar groups of that membrane. If the ion loses water molecules from its hydration shell to another ion or to an electrostatic field, that ion also becomes polarized (by the coordination layer), adopting the same charge (sign) as the polarized water molecules adsorbed in the polar groups of the pore membrane. The ion is then repelled, and does not penetrate (ionic antagonism) since the reflection coefficient equals 1.

The cellular membrane plays the role of regulator of the hydration level of solutes that penetrate the plant. Frequently, the ions do not penetrate through the membrane

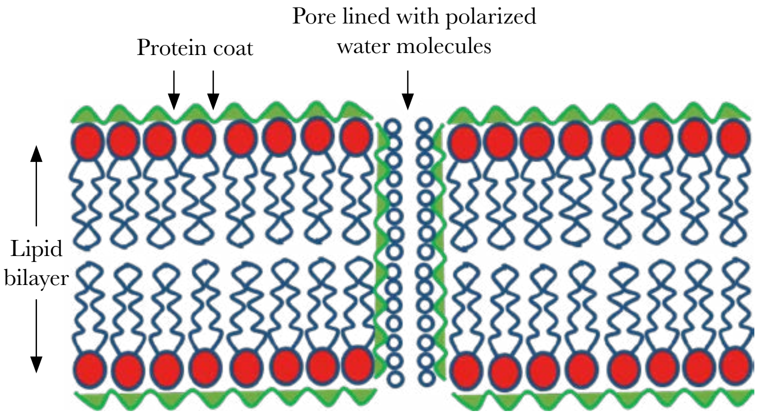

Figure 2. Danielli-Davson (1935) model of the biological membrane, modified to include hydrophilic pores, lined by a layer of polarized water molecules with ice-like structure.

when the soil solution is highly concentrated (saline soils) and the ions just have their minimum hydration shell, which only allows them to remain in solution (Singer and Nicolson, 1972; Aceves, 2011). If ions are found in a diluted solution, as is the case of most soils, the water molecules of their envelopes (distortion layer) can orientate and form hydrogen bonds with the water retained by the membranes in the ice-like structure. This allows the ion to pass through the membrane without being repelled. Hydrated ions always move spontaneously through cell membranes from higher to lower water content on their shells, by diffusion, spontaneous process, without the need of active transport, without ion carriers (Aceves, 2011).

After going through a biological membrane, depending on their charge density, ions can increase or decrease their hydration shells when shared or transferring water molecules; either, interacting with hydration layers of other ions of the internal solution, or with water molecules adsorbed in the tissues. By this means, they obtain or lose mobility inside the plant. Generally, for an ion or organic compound to move through the tissues of any living organism, it must have a minimum required degree of hydration to keep it in solution. That is why membranes become impermeable only when ions do not have the necessary hydration shell to neutralize the electrostatic charges of the polarized water molecules on the inside of membrane pores. In regard to the ion, the degree of selectivity of a membrane depends on its degree of hydration (Green, 1966; Singer and Nicolson, 1972).

New theory proposal

This proposed theory considers that the mechanism of sap ascent in plants, especially in very tall trees, is operating in a permanent and continuous way from the time when seed germinate until the tree reaches considerable heights.

The assumption is that, as the plant grows, one layer of water and one solution column start developing. This layer is formed inside conductive vessels, cell membranes, and tissues by immobile permanent adsorbed water molecules, solutes free, strongly polarized with ice-like structure. This polarized water layer keeps growing together with the plant. This is not a process occurring suddenly, but a continuous and permanent forming layer in all the tissues, during the entire life of the plant (Aceves, 1994; 2011).

The column is formed by mobile solution transporting plant nutrients inside the xylem, it is retained against gravity force by hydrogen bonds formed with the electrostatic charges existing in the permanent layer of polarized water molecules. Due to this, the mobile column is not subject to any acting tension force, produced by plant transpiration; therefore, no cavitation occurs inside the xylem because the only acting forces on the solution column are electrostatic.

This fact is fundamental to understand why no hydrostatic gradients exist that are produced by gravitational water inside the tree, so, no solution gushes out when a trunk is perforated.

The water molecules contained in a mobile solution inside trees, which it is formed by the hydration shells of the solutes, together with the bulk water molecules are in permanent exchange in all directions, in response to the existing electrostatic charges and water content in the tissues. All the solutes move through the cell membranes and in the conductive vessels with their hydration shells. Hydrogen bonds, supporting the whole mobile column by electrostatic forces, can be measured with the pressure chamber designed by Scholander (1958). As thin are the ions hydration shells, the bigger is the retention force due to electrostatic forces. The Scholander pressure chamber measures varies as a function of the water content in the conductive vessels.

The mobile water column is broken when the supplying of the water volume from the soil to the root of a plant occurs at a lesser velocity and amount than that which is lost through transpiration. The plant withers and the continuity of its solution column is broken. When the water level of the soil solution increases again and the bulk water comes into contact with the roots jointly with the hydrated ions, water molecules that do not form part of hydration shells go through with the help of a transport mechanism generated by the tremendous electrostatic potential existing inside roots (acting as water drag force). These hydration envelopes together with hydrated ions that entered the membrane are exchanged from one point to another in an ascending chain process that regenerates the column of the mobile solution, independently of whether the transpiration and metabolic processes are at very low levels. This mechanism upwards, even in conditions of reduced metabolism, is the cause of the appearance of the capillarity phenomena, root pressure, guttation, and exudation of solution in severed stems of trunks. In addition, this mechanism is the cause of the existence of air and water vapor inside the plant ducts, without risking the column of solution would not be reestablished.

When the leaves lose water through transpiration and metabolic process, the water content in the mobile solution decreases inside the upper part of conductive vessels, the electrostatic charges existing in the permanent layer of immobile polarized water molecules show a behavior like small magnets, producing an electrostatic chain reaction by mean of hydrogen bonds, carrying the mobile solution upward, avoiding problems of cavitation and tensile strength; also forming an electrostatic potential gradient inside the conductive vessels and tissues from the leaves to the roots. At the same time a matric water potential is formed from higher to lower water content, from the root to the leaf. The sum of those potentials acting together are what produces the driving force carrying the whole mobile water column upward in small plants and high trees.

It is worth emphasizing that the proposed theory herein stated considers the review of a series of theoretical analyses in regard to molecular form and structure of water and its behavior in all hydration and dehydration reactions, occurring in ions, soil minerals, and physical and biological processes inside the whole plant. It is based on other existing theories and published known facts that have been demonstrated, and accepted as valid, that were cited above in this document. To which we can add Sterling (1966), Garrison and Anderson (1975), Tyree (1997), Canny (1998), Stiller and Sperry (1999), Koch *et al.* (2004), Podgornik (2012), Kumar (2016), and Chaplin (2018).

CONCLUSIONS

The proposed theory states that as the plant grows, a layer of water and a column of particular-behavior solution begin to develop. The water layer is formed within the conductive vessels by permanently immobile, solute-free, strongly polarized adsorbed water molecules with an ice-like structure. The layer of polarized water continues to grow along with the tree. This is why water can ascent in trees taller than one-hundred meters.

REFERENCES

Aceves, N. E. 1994. Scientists underestimated water. Colegio de Postgraduados. México. 53 pp.

Aceves, N.E. 2011. El ensalitramiento de los suelos bajo riego: Identificación, control, combate y adaptación. Colegio de Postgraduados. México. 123-158p.

Azcón-Bieto J, Talón M. 2008. Fundamentos de Fisiología Vegetal. Madrid, McGraw-Hill/Interamericana. Universitat de Barcelona.

Bernal, J. D. 1965. The structure of water and its biological implications. In Symposia of the Society for Experimental Biology 19: 17-32p.

Canny, M.J. 1998. Applications of the compensating pressure theory of water transport. *Am. J. Bot 85*(7): 897-909p.

Chaplin, M. 2019. Water structure and science. 2016. URL https://water. lsbu. ac. uk/water/water_vibrational_spectrum. html.

Danielli, J.F., H. Davson. 1935. A contribution to the theory of permeability of the thin films. *Journal of Cellular and Comparative Physiology 5*(4): 495-508p. https://doi.org/10.1002/jcp.1030050409.

Dang, L.X., J.E. Rice., J. Caldwell., P.A. Kollmad. 1991. Ion solvation in polarizable water: Molecular dynamics simulations. *J. Am. Chem. Soc 113*(7): 2481-2486p.

Dhopatkar, N., A.P. Defante., A. Dhinojwala. 2016. Ice-like water supports hydration forces and eases sliding friction. *Science Advances 2*(8): 1-10p.

Garrison, S., D.M. Anderson. 1975. Infrared study of exchangeable cation hydration in montmorillonite1. *Soil Sci. Soc. Amer. Proc 39*(6): 1095-1099p.

Gouin, H., W. Kosinski. 1998. Boundary conditions for a capillary fluid in contact with a wall. *Archives of Mechanics* 50: 907-916p.

Green, D.E., J.F. Perdue. 1966. Membranes as expressions of repeating units. *Biochemistry* 55: 1295-1302p.

Kim, J., G. Kim., P.S. Cremer. 2001. Investigations of water structure at the solid/liquid interface in the presence of supported lipid bilayers by vibrational sum frequency spectroscopy. *Langmuir 17*(23): 7255-7260.

Koch, W., S.C. Sillett., G.M. Jennings., S.D. Davis. 2004. The limit to tree height. *Nature* 428: 851-854p.

Kropman, M.F., H.J. Bakker. 2001. Dynamics of water molecules in aqueous solvation shells. *Science 291*(5511): 2118-2120p.

Kumar, S. 2016. Ascent of Sap in Plants: Experiment and Theories Botany. Biology. Discussion. http://www.biologydiscussion.com/plants/ascent-of-sap/ascent-of-sap-in-plants-experiment-and-theories-botany/14920.

Lyubartsev, A.P., A. Laaksonen. 1996. Concentration effects in aqueous NaCl solutions. A molecular dynamics simulation. *Phys. Chem* 100: 16410-18p.

Marcos, Y. 2012. Implicaciones biofísicas. En: Iones en el agua e implicaciones biofísicas. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-4647-3_5

Oertli, J.J. 1971. A whole-system approach to water physiology in plants. *Adv. Frontiers of Plant Sci.*, New Delhi, India.

Ohe, C., Y. Goto., M. Noi., M. Arai., H. Kamijo., K. Itoh. 2007. Sum frequency generation spectroscopic studies on phase transitions of phospholipid monolayers containing poly (ethylene oxide) lipids at the air−water interface. *The Journal of Physical Chemistry B 111*(7): 1693-1700.

Podgornik, R. 2012. Water: The Forgotten Chemical, Edited by Denis Le Bihan and Hidenao Fukuyama. PanStanford Publishing, Singapore (2011), 399 pages.

Scholander, P.F. 1958. The rise of sap in lianas. The physiology of forest trees 3-17p.

Smolin, N., V. Daggett. 2008. Formation of ice-like water structure on the surface of an antifreeze protein. *The Journal of Physical Chemistry B 112*(19): 6193-6202.

Sposito, G.; Prost, R. 1982. Structure of water adsorbed on smectites: chemical reviews. *American Chemical Society* 82: 553-573p.

Singer, S.J., G.L. Nicolson. 1972. The fluid mosaic model of the structure of cell membranes. *Science 175*(4023): 720-731.

Stiller, V., J.S. Sperry. 1999. Canny's compensating pressure theory fails a test1. *American Journal of Botany 86*(8): 1082-1086p.

Tyree, M.T. 1997. The cohesion-tension theory of sap ascent: current controversies. *Journal of Experimental Botany 48*(10): 1753-1765p.

Viswanath, P., H. Motschmann. 2008. Effect of interfacial presence of oriented thiocyanate on water structure. *J. Phys. Chem. C 112*(6): 2099-2103.