Team number 349

problem select：A

Model of decreasing atmospheric pressure over time after evaporation of polar caps and subsurface ice

November 7, 2021

Abstract

For a long time, as the solar wind and particles escape, the atmosphere is decreasing.Suppose we can by evaporation polar ice cap and the underground, to increase the air pressure on the surface of Mars to 0.2 bar.In the process, the polar ice cap and the underground evaporation mainly by raising the content of water vapor in the atmosphere of carbon dioxide and the atmospheric pressure.Due to the small magnetic field inside the planet and the smaller gravity, the Martian atmosphere continuously escapes into outer space under the action of solar wind and particle escape.

Through thermodynamics and statistical physics, we establish a model of atmospheric pressure decreasing with time.According to the relationship between pressure and microscopic quantity,the law of atmospheric pressure changing with time is revealed. Based on the estimated polar cap and subsurface ice area, it is estimated that it will take about 700 million years for atmospheric pressure to decrease from 0.2bar to 0.1bar.Based on estimates of polar caps and subsurface ice and their composition, we model the relationship between atmospheric pressure and atmospheric particle count on Mars.At the same time, the relationship between the number of atmospheric escaping particles and the change of atmospheric pressure is estimated, so as to establish a basic model for the change of atmospheric pressure over time. After establishing the model, we further modified the model for the change of air temperature and g with the increase of altitude.

CONTENTS

1. Introduction

1.1. Background

Mars is believed to have lost much of its surface water 3.5 billion years ago, but the amounts that escaped into space and remain frozen in the crust today are not well known[2].Mars used to have an atmosphere rich in water and carbon dioxide, which made it warm and wet, according to current research. As the planet's atmosphere escaped into outer space, mainly due to factors such as the solar wind, the atmosphere became thinner and thinner, so that Mars is now cold and dry.

1.2. Polar caps and underground ice

The European Space Agency's Mars Express Made Observations with its OMEGA discovered that the Southern Ice Cap, existing all year round.Northern cap could be a mixture of water and carbon dioxide, while northern cap could be composed of water ice.The results also showed that hundreds of square kilometers of permafrost surround the south pole. Permafrost is water ice, mixed into the soil of Mars, which frozen to the hardness of solid rock due to the low Martian temperatures.[3] In addition, the original atmosphere of Mars is composed of 96% carbon dioxide, so if the polar cap and groundwater were all evaporated, the atmosphere would be composed mainly of carbon dioxide and water.

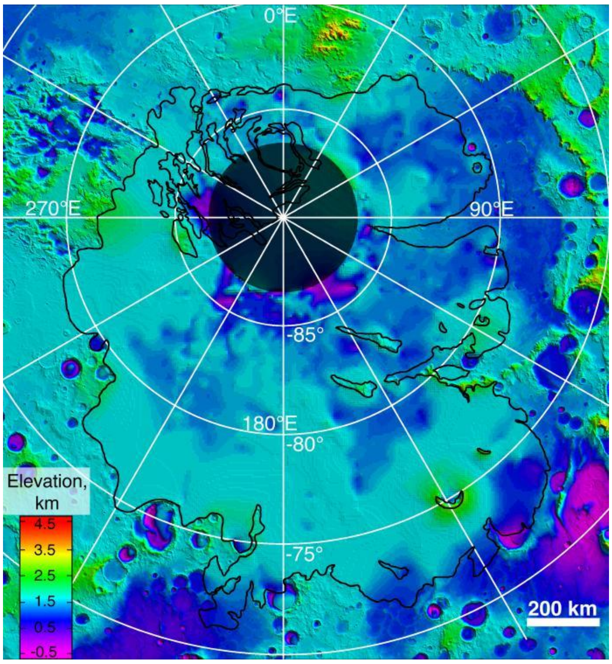

Figure1：Lower boundary of icy layers covering Mars' south-polar region[4]

1.3. Solar wind

The solar wind is a stream of particles, mainly protons and electrons flowing from the sun's atmosphere at a speed of about one million miles per hour. The magnetic field carried by the solar wind as it flows past Mars can generate an electric field. This electric field accelerates electrically charged gas atoms, called ions, in Mars' upper atmosphere and shoots them into space. Using data collected by MAVEN, researchers have determined that the current speed at which Mars's atmosphere escapes rate from the solar wind is about 100g/s. [5]

1.4. The Martian magnetic field

One method commonly thought to help protect planetary atmospheres is through an internally generated magnetic field, such as Earth which deflects charged particles in the solar wind away from the Sun, creating a protective bubble magnetosphere around the planet.[6]According to the comparative study between Mars and Earth, Mars is believed to have a metal core, and it is predicted that Mars should have a medium strong magnetic field (about 10%~15% of the Earth's magnetic field), but spacecraft only detected a weak magnetic field, its intensity is 0.1%~0.2% of the Earth's magnetic field, so the blocking effect of Mars magnetic field on solar wind is extremely weak.

1.5. Small gravitational binding

Martian quality is close to one-tenth of the earth, Mars is about half of the earth's radius radius.The low gravity affects the size of the molecules' escape velocity, the Martian escape velocity of about 5.03 km/s, at the same time the solar wind of charged particles hit the molecules in the atmosphere, let the molecules have higher speed, making a lot of gas escape out of the atmosphere.

2. Assumptions and Symbols

2.1. Assumptions

To advance our analysis, firstly, we stand upon some reasonable assumption of simplify the greater complexity of the problem：

1. Since the density of the Martian atmosphere is low and the density of the upper atmosphere is even lower, we will only discuss the lower atmosphere (the region where most atmospheric molecules are present) .Here, we assume that the height of the atmosphere does not change as the atmospheric pressure drops from 0.2bar to 0.1bar.
2. Due to the low content of gases such as argon, nitrogen and methane in the Martian atmosphere, we consider the composition of the atmosphere as a mixture of water and carbon dioxide.
3. In the process of problem analysis, we take Mars as a sphere without considering the influence of Mars' climate, landform and other internal factors on pressure reduction.
4. Ignoring the separate escape of water after decomposition into H and O and the complex process of various ion escape.It is simplified to the process of water directly escaping to outer space without deliberately distinguishing the specific escape of water and carbon dioxide.
5. Since the dissipation time of Mars atmosphere is longer than that of extreme conditions (such as solar storm, etc.), we take the average value of atmospheric dissipation and ignore the interference of extreme conditions on Mars atmospheric dissipation.

2.2. Notations

Symbol	Definition
n	Total molecules of water and carbon dioxide
g	Acceleration of gravity on Mars
R	The radius of Mars
k	Boltzmann constant
P_0	The pressure is the atmospheric pressure right after vaporizing the polar cap and the underground ice
N_A	Avogadro's constant
M_{H2O}	The molar mass of water
M_{CO2}	The molar mass of carbon dioxide
T	Surface temperature of Mars
ω	The ratio of the number of carbon dioxide molecules to the number of water molecules
λ_1	The number of water molecules escaping per second
λ_2	Number of carbon dioxide escapes per second
m	The molecular mass of the atmosphere at time t
v	Atmospheric mass per unit time carried away by the solar wind

3. Model

3.1. The relationship between atmospheric pressure and the number of molecules in the Martian atmosphere

According to thermodynamics and statistical physics, atmospheric pressure on the surface of Mars is caused by the gravity of Mars in the upper atmosphere. Under the gravity of Mars, the molecular density in the atmosphere shows a dense arrangement of molecules at the bottom and dense arrangement of molecules at the top, and it shows an exponential decline in the atmosphere as follows：

$$\rho = \rho_0 \, e^{\frac{-mgh}{kT}}$$

Where ρ is the molecular number density per unit area of a point above Mars at a height of H,ρ_0 is the molecular density per unit area of the surface. We assume that the gravitational acceleration g is a constant value in the atmospheric range studied. Therefore, by integrating, we can obtain the total number of molecules per unit area contained in the air column from the surface to the atmospheric boundary, i.e:

$$\int_0^H \rho_0 \, e^{\frac{-mgh}{kT}} dh$$

In this way, we can through the atmospheric molecular average relative molecular mass and Avogadro constant per unit area corresponding to the air column by gravity, which can get the pressure on the surface of Mars.Because the universe such as atmospheric molecular number by the solar wind over time and decreasing the influence of external conditions, it can get air internal number of molecules and the changes of time.And we just figured out the relationship between the pressure and the number of molecules, so we can figure out how the pressure changes over time.

3.2. The analysis of model building

3.2.1. Elimination of distractions

By estimating the volume of polar caps and subsurface ice on Mars and estimating the current dissipation rate of the Martian atmosphere, it can be concluded that the atmospheric pressure of 0.2bar decreases to 0.1bar over a long period of time.So we can rule out some short-term interference factors.Changes in the planet's internal system, such as changes in Martian terrain, landform and climate, as well as changes in the cosmic external environment, such as solar storms and other celestial disturbances on Mars, can accelerate the escape of the Martian atmosphere to a certain extent. However, compared with the influence of the solar wind and other major factors, the impact is relatively weak. We will not make special discussions here.

3.2.2. Effects of solar wind on Atmospheric escape from Mars

At Mars and the Earth solar near-UV radiation penetrates sufficiently deep into the atmospheres to dissociate H2O, and the resulting H and O atoms then diffuse into the upper atmosphere. Both H and O atoms may be lost into space, H by both Jeans' escape and non-thermal processes, and the heavier O mainly by non-thermal processes.The main processes for atmospheric evaporation from the top of the martian atmosphere are thermal or Jeans' escape, non-thermal escape from photochemical processes, ion escape and outflow and ion sputtering.[7]

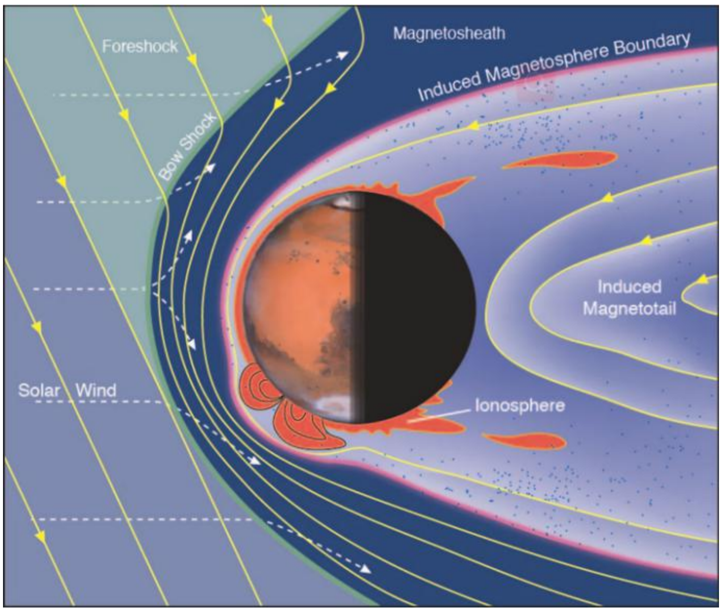

Figure2：Illustration of the global plasma interaction between Mars and the solar wind. Various plasma boundaries and regions are described.[8]

3.3. Modeling

There are many distractions in the modeling process, but we will only take the most important ones.The solar wind is responsible for the erosion of the atmosphere of Mars, according to the data form NASA ,the solar wind takes away 100 grams of Martian atmosphere per second.After avoiding some unnecessary factors, the knowledge of thermodynamics and statistical physics is used to build the model.The basic parameters of Mars are as follows：

physical quantity	numerical value
Mass(M)	6.4171×1023 kg
Diameter(D)	6779 km
surface temperature(T)	210 K
mean radius(R)	3389.5 km

We assume that the composition of 0.2bar Martian atmosphere is mainly composed of carbon dioxide and oxygen, and the total molecular number is N, among which the molecular number of water is X. The molecular number of carbon dioxide is N-X, and the solar wind is the main reason that affects the reduction of Martian atmosphere. The change relationship between the molecular number of water and carbon dioxide over time is linear.
Assuming that the starting:

$$\omega=\frac{N-X}{X}$$

$$X=\frac{N}{\omega+1}$$

$$N-X=\frac{N\omega}{\omega+1},$$

The number of water molecules decays over time:

$$\frac{N}{\omega+1}-\lambda_1 t$$

The change in the number of carbon dioxide molecules over time

$$\frac{N\omega}{\omega+1}-\lambda_2 t$$

According to Newton's law of gravity, the gravitational pull on an object of mass M_1 on the surface of Mars:

$$m_1 g=G\frac{Mm_1}{R^2}$$

The gravitational acceleration of Mars is obtained as $g=3.727m/s^2$, in which the gravitational constant $g= 6.67259*10^{-11}\ Nm^2/kg^2$, m is the mass of Mars,R is the radius of Mars,m_1 is the mass of an object near Mars.We also need the distribution of the molecules in the Martian atmosphere to vary with height based on other pressure characteristics. You take a cylinder, the molecular density n at height Z, the pressure P(Pa).

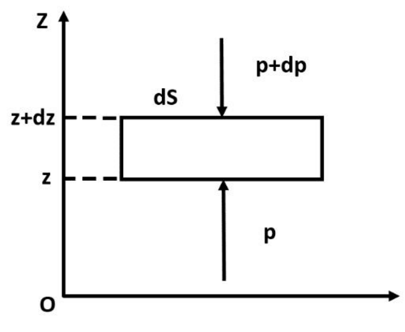

Figure3：Schematic diagram of differential method

So here we have the differential equation

$$(P+dp)dS+dzdSn=PdS$$

Acquire:

$$P = P_0 e^{-\frac{mgz}{kg}}$$

P_0 is the atmospheric pressure on the surface of Mars at time t=0. Generation into the formula:

$$P = n\,k\,T$$

Acquire:

$$N = n_0\, e^{\frac{-mgz}{kT}}$$

We consider that the radiation absorbed by Mars in its orbit around the sun is a constant value, so we calculate the average temperature of Mars T=210K At the same height, the gas distribution is the same, and the height of the atmosphere is H. We adopt the element method. On the unit area of Mars, we take a column of dz at the height z, and the gas in the column is approximately in equilibrium if dz is small enough

$$dn = n_0\, e^{\frac{-mgz}{kT}} dz$$

At time t, I integrate with respect to height z

$$\int_0^H n\, e^{\frac{-mgz}{kT}} dz = \frac{N-(\lambda_1+\lambda_2)t}{S}$$

get N

$$P = nkT$$

$$P = \frac{N-（\lambda 1+\lambda 2）t}{4\pi R^2（1-e^{\frac{-mgH}{kT}}）} mg \ (1)$$

N is the molecular density on the surface of Mars at time T, m is the molecular mass, k is Boltzmann constant, and S is the surface area of Mars. Where m is a function of t

$$m = \frac{（\frac{N}{\omega+1}-\lambda_1 t）M_{H_2O}+（\frac{N\omega}{\omega+1}-\lambda_2 t）M_{CO_2}}{N_A\,[N-（\lambda_1+\lambda_2）]} \ (2)$$

M water is the molar mass of water, M carbon dioxide is the molar mass of carbon dioxide, and N_A is Avogadro's constant.

We have the constant H at time t=0

By the formula at t=0 , $\int_0^H n\, e^{\frac{-mgz}{kT}} dz = \frac{N-(\lambda_1+\lambda_2)t}{S}$available

Acquire:

$$\int_0^H n\, e^{\frac{-mgz}{kT}} dz = \frac{N}{S}$$

among n=n0,m=m0
Acquire:

$$H=-\frac{KT}{gm_0}\ln(1-\frac{gNm_0}{4\pi R^2 P_0})$$

Where m0 is the molecular mass at time zero,
The decay equation of the Martian atmosphere

$$P=\frac{N-(\lambda 1+\lambda 2)t}{4\pi R^2(1-e^{\frac{-mgH}{kT}})}mg \quad (1)$$

$$m=\frac{(\frac{N}{\omega+1}-\lambda_1 t)M_{H_2O}+(\frac{N\omega}{\omega+1}-\lambda_2 t)M_{CO_2}}{N_A[N-(\lambda_1+\lambda_2)]} \quad (2)$$

Where λ_1 and λ_2 are related to atmospheric components and depend on the relationship between carbon dioxide and water in the atmosphere:

$$\lambda_1=\frac{M_{H_2O}NN_A}{M_{H_2O}+M_{CO_2}\omega}$$

$$\lambda_2=\frac{N\omega N_A M_{CO_2}}{M_{H_2O}+M_{CO_2}\omega}$$

Where ω is the ratio of the number of carbon dioxide molecules to the number of water molecules.

4. Model solving and analysis

According to our decay model, if we want to solve the exact time t, we have several values to determine: ω, the ratio of the number of carbon dioxide molecules to the number of water molecules; λ_1, the decay coefficient of water molecules; λ_2, the decay coefficient of carbon dioxide molecules; and N, the total number of Martian polar ice caps and subsurface ice.
For λ_1 and λ_2, we only take the analysis of solar wind, which plays a major role in particle escape. At present, the escape rate of particles in the Martian atmosphere is v=100g/s under the atmospheric condition of 0.006bar. We temporarily assume that the particles dissipated in the Martian atmosphere under the action of solar wind are only related to the molecular density of Martian atmosphere. In addition, the formula p=nkT shows that atmospheric pressure is proportional to atmospheric molecular density (the atmosphere is only composed of atmospheric molecules), so the diffusion rate of atmospheric molecules at pressure P can be given.

V=p*10^5/6

It can be seen that when the pressure is 0.2bar, V1 =3333g/s. And when the pressure drops from 0.2bar to 0.1bar, the particle escape amount per unit time changes with time. According to the MAVEN observation data, the polar cap and the composition of the underground ice, give priority to with water and carbon dioxide, but accounts for most of the water. So we can set the ω value at 1/9, which means 21.36% carbon dioxide mass and 78.64% water mass. In that case, we identified by means of approximate estimates of atmospheric composition. Due to the depth of underground ice cap is unknown, to determine the total number of molecules in the polar ice caps and groundwater according to the Plot and others guess, underground ice melting ice caps of Mars after 11 m we can cover the surface of Mars on the basis of the number of molecules roughly calculate the polar cap and groundwater at about 4.98*10 ^ 43. So, the N and ω is roughly calculated and estimated.
By substituting N=4.98 10^43 and ω=1/9 into the following equations,

$$P = \frac{N - (\lambda 1 + \lambda 2)\, t}{4\pi R^2\left(1 - e^{\frac{-mgH}{kT}}\right)} mg$$

$$m = \frac{\left(\frac{N}{\omega + 1} - \lambda_1 t\right) M_{H_2O} + \left(\frac{N\omega}{\omega + 1} - \lambda_2 t\right) M_{CO_2}}{N_A\left[N - (\lambda_1 + \lambda_2)\right]}$$

As the atmospheric particles escape, the pressure decreases as there are fewer particles in the atmosphere. We ignore changes in the height of the atmosphere.In this process, we make ω=1/9, that is, 21.36% of the mass of carbon dioxide and 78.64% of the mass of water as reasonable assumptions for the model.
It has been approximately proved that we can establish the relationship between particle escape per unit time and atmospheric pressure by the relationship between atmospheric particle density and atmospheric pressure.

$$v = \frac{p}{6}$$

We have previously deduced the relation between λ_1 ,λ_2 and v

$$\lambda_1 = \frac{vN_A}{M_{H_2O} + M_{CO_2}\omega}$$

$$\lambda_2 = \frac{v\omega N_A}{M_{H_2O} + M_{CO_2}\omega}$$

Now v is substituted into the system of equations and sorted out with (1) and (2)

$$P = \frac{N - (\lambda_1 + \lambda_2)\, t}{1 - e^{\frac{-\left(\frac{N}{\omega+1} - \lambda_1 t\right) M_{H_2O} + \left(\frac{N\omega}{\omega+1} - \lambda_2 t\right) M_{CO_2} gH}{N_A\left[N - (\lambda_1 + \lambda_2)\right] kT}}} \frac{mg}{4\pi R^2}$$

This is the implicit function equation of P and T. We used MATLAB to pick points for many times to describe the curve of atmospheric pressure change over time on Mars.

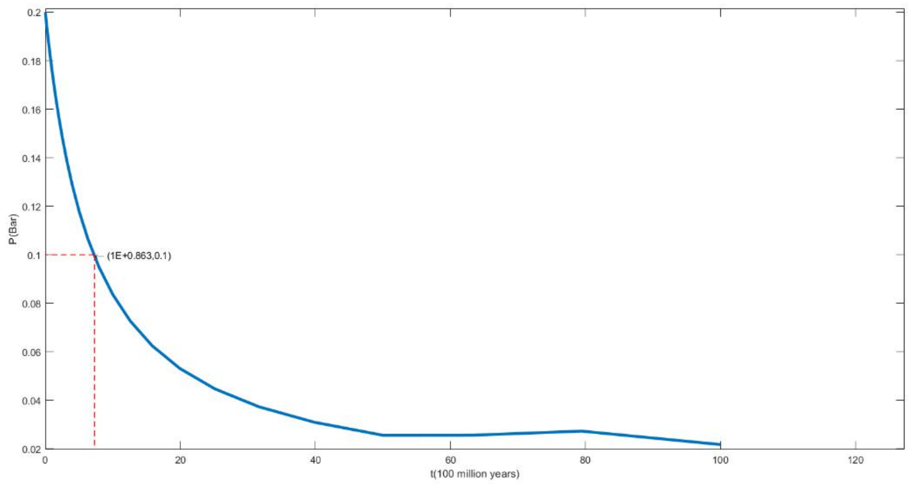

Figure4：The prediction of time changes of Atmospheric pressure on Mars by MATLAB

As can be seen from the figure,atmospheric pressure decreases at a slower rate over time.When atmospheric pressure drops to 0.1bar, it takes $3* 10^{15.863}$ seconds, that is, about 700 million years.

5. Modifications to the model

5.1. Modification of T in the model

In the previous discussion, we assumed that the temperature of the Martian atmosphere was a constant T and evenly distributed. However, that model can only do some rough estimates, which had a good fitting for a shorter period of time. But there might be a big error in the model if we extend the length of time, and that's why we make corrections for temperature.
By referring to the results that fitting data of Mars-Gram conducted by Ushijima, a Japanese National University ‘s researcher, in 2010:

$$T=241.0-0.999(h/1000) ,h<7000m$$

$$T=249.5-2.22(h/1000),h\geq 7000m$$

We can correct the previous model and give 4 new formulas below:

$$\mathbf{p}=\frac{\mathbf{241k[N-(\lambda_1+\lambda_2)t]}}{\mathbf{S[\int_0^{7000} e^{\frac{mgz}{k(0.000999z-241)}}dz+\int_{7000}^{H} e^{\frac{mgz}{k(0.000999z-241)}})dz}}$$

$$\mathbf{V=p*10\text{^}5/6}$$

$$\mathrm{m}=\frac{\left(\frac{\mathrm{N}}{\omega+1}-\lambda_1 t\right)\mathrm{M}_{\mathrm{H_2O}}+\left(\frac{\mathrm{N}\omega}{\omega+1}-\lambda_2 t\right)\mathrm{M}_{\mathrm{CO_2}}}{\mathrm{N_A}\left[\mathrm{N}-\left(\lambda_1+\lambda_2\right)\right]}$$

$$\lambda_1=\frac{\mathrm{vN_A}}{\mathrm{M_{H_2O}}+\mathrm{M_{CO_2}}\omega}$$

$$\lambda_2=\frac{\mathrm{v}\omega\mathrm{N_A}}{\mathrm{M_{H_2O}}+\mathrm{M_{CO_2}}\omega}$$

5.2. Modification of g in the model

In the previous model, we set g as a constant that does not change with altitude. However, in practical problems, g decreases with altitude, and the connection between g and altitude is

$$\mathrm{g}=\frac{\mathrm{MG}}{\mathrm{R}^2}$$

Therefore, the modified g is substituted into the formula above, and we can make a further modification of the formulas mentioned in 5.1:

$$\mathbf{p}=\frac{\mathbf{241k[N-(\lambda_1+\lambda_2)t]}}{\mathbf{S[\int_0^{7000} e^{\frac{MGmz}{k(R+z)^2(0.000999z-241)}}dz+\int_{7000}^{H} e^{\frac{MGmz}{k(R+z)^2(0.000999z-241)}})dz]}}$$

The v, m, λ_1, λ_2 are the same as those in 5.1.
By establishing those two corrections, we further considered the changes of temperature and the vary of gravity acceleration on Mars with altitude on the initial model, which further fitting the real atmosphere of Mars.

6. Discussion

To establish the model, we establish a Martian atmosphere molecular number attenuation equation according to the gas dynamic theory and the thermodynamics theory. We make a lot of approximations so that the equation only works under ideal conditions, and we can roughly estimate the variation of the Martian atmosphere, but this requires a lot of error.

6.1. Advantages

We build the model through thermodynamics and statistical physics, and establish the relationship between micro and macro to get the change rule of atmospheric pressure over time.In this process, we estimate the relationship between atmospheric pressure and particle escape per unit time.In addition, we have made reliable estimates on the composition and volume of Mars polar caps and underground ice and established a visual model with MATLAB to fit the rule of atmospheric pressure changing over time.

6.2. Disadvantages

Defects of the model is ignored by the factors, we set the Martian surface temperature equal everywhere, the height of the atmosphere of Mars is a constant value, the source of the gas mass loss of the solar wind and ignoring the other factors, such as atmospheric molecules to escape in space and a thermal process of molecules (such as sputtering, photochemical change),The erosion of The Martian atmosphere by solar wind is proportional to the number of atmospheric molecules and changes with the acceleration of gravity at altitude. If we take these factors into account in our model, our model will be further modified to better fit the changes in the Martian atmosphere.

7. Conclusion

Through statistical physics modeling, we found that the rate of atmospheric pressure loss slowly decreases over time, resulting from the thinning of the atmosphere.It took us about 700 million years to go from 0.2bar to 0.1bar and in addition to that, we corrected for the acceleration of Gravity on Mars and the effect of temperature on the model.

8. Reference

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[2],[4],[7]J. T. Clarke1 , J.-L. Bertaux1,2, J.-Y. Chaufray2 , G. R. Gladstone3 , E. Quemerais2 , J. K. Wilson4 , and D. Bhattacharyya1. A rapid decrease of the hydrogen corona of Mars.
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[5] William Harwood. Solar wind is blowing away the atmosphere on Mars. November 5, 2015 / 4:41 PM / CBS NEWS.
[6],[8] Leaky atmosphere linked to lightweight planet ESA / Science & Exploration / Space Science / Mars Express. 08/02/2018

9. Appendix

```
g=3.727;
R=3389.5e3;
K=1.380649e-23;
T=210;
p0=20000;
NA=6.02e23;
M_H2O=18e-3;
M_CO2=44e-3;
G=6.67e-11;
M=6.4171e23;

P_guess=20000;
P_list=zeros(1,180);
t_list=zeros(1,180);

omega=1/9;

n=4.98e43;


%-------------------------


tmpP=20000;

for dt = 0.1:0.1:18

    t=3*10.^(dt-1)-3;
    t_list(int16(dt*10))=t;
    P_guess=tmpP;
```

```
    while(1)
        %------normal------

lambda_1=(P_guess.*M_H2O)./(M_H2O+omega.*M_CO2).*10.^23.*1.0033;

lambda_2=(P_guess.*omega.*M_CO2)./(M_H2O+omega.*M_CO2).*10.^23.*1.0033;
        m=
((n/(omega+1)-lambda_1*t)*M_H2O+((n*omega)/(omega+1)-lambda_2*t)*M_CO2)
/ (NA*(n-(lambda_1+lambda_2)*t));
        Right=(n-(lambda_1+lambda_2).*t).*m.*g./ (4.*pi.*R.*R.*(1-(1-
((omega.*M_CO2+M_H2O).*g.*n)./(4.*pi.*R.*R.*p0.*(omega+1).*NA) ).^((m.*(ome
ga+1).*NA)./(omega.*M_CO2+M_H2O)) ));
        delta=P_guess-Right;
        %------plus 10-----
        P_guess=P_guess+1e-3;

lambda_1=(P_guess.*M_H2O)./(M_H2O+omega.*M_CO2).*10.^23.*1.0033;

lambda_2=(P_guess.*omega.*M_CO2)./(M_H2O+omega.*M_CO2).*10.^23.*1.0033;
        m=
((n/(omega+1)-lambda_1*t)*M_H2O+((n*omega)/(omega+1)-lambda_2*t)*M_CO2)
/ (NA*(n-(lambda_1+lambda_2)*t));
        Right=(n-(lambda_1+lambda_2).*t).*m.*g./ (4.*pi.*R.*R.*(1-(1-
((omega.*M_CO2+M_H2O).*g.*n)./(4.*pi.*R.*R.*p0.*(omega+1).*NA) ).^((m.*(ome
ga+1).*NA)./(omega.*M_CO2+M_H2O)) ));
        deltap10=P_guess-Right;
        %-----minus 10-----
        P_guess=P_guess-2e-3;

lambda_1=(P_guess.*M_H2O)./(M_H2O+omega.*M_CO2).*10.^23.*1.0033;

lambda_2=(P_guess.*omega.*M_CO2)./(M_H2O+omega.*M_CO2).*10.^23.*1.0033;
        m=
((n/(omega+1)-lambda_1*t)*M_H2O+((n*omega)/(omega+1)-lambda_2*t)*M_CO2)
/ (NA*(n-(lambda_1+lambda_2)*t));
        Right=(n-(lambda_1+lambda_2).*t).*m.*g./ (4.*pi.*R.*R.*(1-(1-
((omega.*M_CO2+M_H2O).*g.*n)./(4.*pi.*R.*R.*p0.*(omega+1).*NA) ).^((m.*(ome
ga+1).*NA)./(omega.*M_CO2+M_H2O)) ));
        deltam10=P_guess-Right;
        P_guess=P_guess+1e-3;

        if(abs(delta)<=1e-12 || ( abs(delta)<abs(deltap10) &&
abs(delta)<abs(deltam10) ))
            tmpP=P_guess;
```

```
            P_list(int16(dt*10))=P_guess;
            break;
        elseif(abs(deltap10)>abs(deltam10))
            P_guess=P_guess-1e-3;
        else
            P_guess=P_guess+1e-3;
        end

    end
    fprintf("i:%E-P:%.15f\n",t,P_guess);
end

hold on;
plot(t_list/3e15,P_list/1e5,'LineWidth',3);
line([1*10^0.863 0],[0.1 0.1],'linestyle','--', 'Color','r', 'LineWidth', 1);
line([1*10^0.863 1*10^0.863],[0.1 0],'linestyle','--', 'Color','r', 'LineWidth', 1);
text(1*10^0.863,0.1, '\leftarrow (1E+0.863,0.1)');

%axis equal;
xlabel("t(100 million years)");
ylabel("P(Bar)")
```