Potential Mechanisms of Atmospheric Loss on Mars

Atmospheres form and evolve during planetesimal accretion and over the lifetime of a planet. Though the mechanisms underlying atmospheric evolution are not yet definitively understood, there is a burgeoning body of scientific literature dedicated to reconciling current observational evidence with the mechanisms thought to be significant in this evolutionary process. In the case of Mars, the disagreements about the evolution of the atmosphere are pronounced. The composition of the primordial atmosphere, its surface pressure, the strength and effect of the early solar flux, and the magnitude of the effect of mechanisms active in accreting or eroding atmosphere have not yet been definitively answered, but are still being widely debated. The one commonality among the majority of the theories of Martian atmospheric evolution is that the Martian atmosphere was once much denser and this dense atmosphere, which created a much warmer, wetter climate on Mars, was lost. This paper critically examines these different theories of atmospheric evolution and the evidence used to justify them.

The present day Martian Atmosphere is composed primarily of carbon dioxide with trace amounts of water, carbon monoxide and nitrogen (McElroy 443) the surface pressure lies somewhere between 5-7 mbars though it varies seasonally, with most sources favoring 7 mbars. (Ahrens 11) The surface temperature is 215 degrees Kelvin. (11) There is also an unknown quantity of carbon dioxide and water trapped in the polar caps, which are composed of carbon dioxide and water, as well as an unknown amount of water and carbonates trapped in the Martian regolith. (Hunten 915) One estimate for the amount of water and carbon dioxide in the regolith is 30 bars water and 20 bars of carbon dioxide respectively. (915) The atmospheric isotope ratios as reported by a number of sources are organized in table 1.

Table 1:

	D/H	15N/14N	129Xe/132Xe	40Ar/36Ar
Hunten	6	1.62		
Anders			2.5	10

Though the values reported differ, all invariably show significant isotopic enrichment, the values are relative to Earth's isotope ratios.

In order for a model of atmospheric evolution to hold up under scrutiny it must predict conditions which are consistent with our observational evidence. This includes accounting for the isotopic enrichment, the present day surface pressure and composition as well as the surface features and evidence of past Martian atmospheric change.

Understanding the initial conditions of the Martian atmosphere is essential to being able to accurately model the effect that different mechanisms would have over time. The impact of many of the mechanisms proposed to have eroded the Martian atmosphere is heavily dependent upon the conditions under which the mechanism was acting.

There is strong evidence for a warmer, wetter Martian climate in the past. Much of this evidence is provided by the morphology of the Martian surface. "Extensive valley networks and outflow channels in the heavily-cratered terrain, eroded crater features, and layered deposits, all point to substantial physical erosion by liquid water on the surface." (Hutchins 14933) Liquid water is unstable today on the Martian surface and would “either freeze or flash into vapor.” (Hunten 915) Therefore in order for liquid water to exist on the surface of Mars the atmospheric conditions would have to be altered drastically from those observed today.

In a primarily carbon dioxide, water based atmosphere, like that of the present Martian atmosphere, the surface pressure of the atmosphere would have to be increased substantially. Estimates for how thick the atmosphere would have to be in order to have a large enough greenhouse to maintain a surface temperature at which liquid water could exist for a substantial period of time range from 1 bar-5 bar. (Vlassopoulos 79) Most authorities use 1 bar of surface pressure in their models since this would be a sufficient condition for liquid water to exist. There are some in the field who contest that a primarily carbon dioxide and water-based atmosphere could ever create a large enough greenhouse effect for liquid water to exist arguing that the condensation of carbon dioxide in the troposphere would generate clouds with a high albedo. These clouds they stipulate would decrease the solar flux reaching the surface thus negating the greenhouse effect. (Galimov 473). This argument though fails to take into account the fact that in addition to decreasing the solar flux incident on the lower levels of the atmosphere and the surface the clouds would effectively prevent electromagnetic radiation in the infrared given off by the planet from escaping. (Crisp 21) Thus even though the clouds were decreasing the solar flux, the trapping of the infrared heat radiated by the planet would be sufficient to negate this decrease and the clouds would not effectively change the greenhouse effect generated by the carbon dioxide atmosphere. (21)

Additional evidence for the presence of a thicker primordial atmosphere is found in the isotopic ratios of elements in the present-day atmosphere. All of these isotope ratios are enriched indicating that some sort of mass selective atmospheric loss mechanism has been effective in the planet's history. (See Table 1) These mass selective atmospheric loss processes could have eroded a substantial fraction of the atmosphere and the isotopic fraction serves as "a means to isolate and quantify loss by sputtering". (Hutchins 14934) How much atmospheric loss these isotopic ratios indicate is not entirely clear since though the process is mass selective the heavier isotopes would have also been lost to some extent over time and the atmosphere could be replenished by different mechanisms. Among these replenishing mechanisms would be atmospheric accretion by small impactors, outgassing through volcanic processes and release of elements adsorbed in the regolith or trapped in the polar caps and in other subsurface reservoirs.

An alternative theory to the thicker carbon dioxide based atmosphere suggests that there was in fact a methane-based primordial Martian atmosphere. There are several pieces of observational evidence that support this. One such piece of evidence is the fact that "the redoxpotential of the mantle has not remained unchanged through geological time and the mantle evolved from an initially reduced to present oxidized state."(Galimov 473) Also no carbonate spectral lines have been detected on the Martian surface. (474) Though this does not necessarily rule out the existence of carbonates on the surface of Mars it does indicate that they may not be as plentiful as many models predict. Had the atmosphere been initially carbon dioxide-based this should have resulted in a great abundance of carbonates present in the regolith. (474) The isotopic ratios found in the SNC meteorites is also inconsistent with a mass selective loss process by which a mass selective loss process by which the atmosphere was sputtered away over time sputtered the atmosphere away over time. The same isotopic ratios are found in both ALH80041 and EETA79001 though the ages of formation are 4.5 billion years ago and 180 million years ago respectively. (473) This indicates that though they are isotopically enriched this isotope enrichment was not ongoing over time as a result of a continuous mass selective loss process such as sputtering. An alternative to sputtering would be “equilibrium isotope fractionation in a system such as CH_4-CO2” (474) Such an equilibrium “is established in full scale geologically instantly provided that an isotope exchange mechanism exists”. (474) If this carbon dioxide were then adsorbed into the regolith to form carbonates then it would explain the enriched carbonates observed in the SNC meteorites. (474) This theory also explains the current isotopic enrichment of carbon in the present-day carbon dioxide based atmosphere since if the initial atmosphere was completely lost to space as many models predict then this enriched ^{13}C would serve as the source of atmospheric carbon. (474)

One proposed mechanism of atmospheric erosion that is used in several of the current models and is largely dependent on the atmospheric conditions under which it is active, is impact erosion. The effect that an impactor has on a planet’s atmosphere is largely dependent on several parameters of the collision. These parameters include the size of the impactor, the size of the planet, the impact velocity and the thickness of the atmosphere. (Ahrens 537) What actually determines whether there is an overall accretional or erosional atmospheric effect is the total energy of impact (537) Small impactors will eject a mass of air similar to that intercepted by the impactor during infall. This atmosphere is accelerated to speeds greater than the escape velocity as a result of this interaction. (Brain 22690) Large impactors eject a substantially greater amount. This effect is due to the fact that “the expanding vapor cloud produced by impact drags ambient atmosphere away from the planet at speeds exceeding the escape velocity”. (22690) Impactors with a radius of 1 atmospheric scale height and larger are considered large enough to cause significant impact erosion. (Ahrens 537) As the impact energy increases due to larger impactors or changes in the other parameters, such as decreasing atmospheric density, so to does the amount of atmosphere ejected. The atmosphere is ejected in a conical distribution around the site of impact and as the energy increases so does the angle this cone subtends. (540) When the energy becomes exceedingly large as in the case where the mass of the projectile equals the mass of the atmosphere above the horizontal tangent, the angle of the cone reaches 90 degrees and the entire atmosphere above the tangent plane will be ejected. (540) For the current Martian Atmosphere an impactor with a diameter of 3 kilometers and an incident velocity of 14 km/s is sufficient to remove a tangent plane (Brain 22690). As soon as the process of atmospheric erosion begins it accelerates since as the atmospheric density decreases so to does the scale height and smaller more numerous impactors will be able to erode the atmosphere. (Ahrens 540)

In order to determine the effect impact erosion would have played over the course of Martian history, Brain and Jakosky combined our current knowledge of past Martian bombardment, as told by the cratering densities, and our understanding of how much each impact would erode the atmosphere over time. In doing so they considered only the effect that impact evolution would have had only since the beginning of the Martian geologic record. Impact erosion before this will not have left a crater record and thus cannot be determined by this method. (Brain 22690) Using a simplified model of impact erosion they determined that crater diameters of four kilometers are evidence of impacts sufficient to have caused erosion of the atmosphere. (22692) One of the conditions necessary to predicting how large the impactors must be in order to cause impact erosion is the surface pressure of the atmosphere. (Ahrens 540) It is not entirely clear based on the work how they arrived at the four kilometer diameter figure without assuming an initial surface pressure. Among the reasons given for the choice were that four kilometers was a sufficiently large crater size that it should not have been substantially eroded as a result of surface processes over the course of the planet yielding statistically reliable results. (Brain 22692). There results indicated that they had calculated the percentage of atmosphere lost independent of the initial surface pressure. These findings though were not well substantiated given the integral way in which impact erosion will depend on the initial atmospheric conditions under which it is acting. This likely could have skewed their results. In addition to this, they used a four kilometer bin size as the necessary crater diameter size over all geologic history not taking into account as the atmosphere became thinner it would be more readily eroded by smaller impactors. (Ahrens 540)

Using these approximations and crater densities from the work of Hartmann et el, Craddock and Maxwell, and Scott and Tanaka they proceeded to determine the effect that impact erosion had on surface pressure as simply a function of crater density and surface pressure independently of time. (Brain 22690) In so doing they found that the Martian atmosphere could have been eroded by a factor of 2.1-8.7. This corresponds to a loss of early atmosphere by large impacts of 50-90%. (22692) These results differed greatly from those determined independently by Melosh and Vickery and according to this method the "crater density would need to be > 0.01 km^{-2} (almost an order of magnitude greater than the highest crater densities listed above)". (22692) The authors also went on to conclude that since the crater density was highest during the Noachian period, impact erosion would have had the largest effects during this period decreasing steadily in the Hesperian and Amazonian. (Brain 22692) Though bombardment was more active during the earlier periods the depletion of the atmosphere would have substantially altered the effectiveness of impact erosion and a sufficient justification for neglecting these effects was not given. Another mechanism whose effect over time is largely dependent upon the conditions of the atmosphere upon which it is operating is sputtering. Sputtering refers to the gradual loss of atmosphere to space due to exceeding the escape velocity. For Thermal or Jean's Escape atoms above the exobase with velocities greater than the escape velocity of the planet, those at the high end of the Maxwellian velocity distribution, will escape into space if their velocity vectors are directed upward and out of the atmosphere. (Hunten 916). The exobase is the level of atmosphere above which the mean free path is longer than the scale height. (Lewis) As the mass of the atom increases it is less likely to be lost to space. This is because a more massive atom would have to have a greater energy or momentum associated with it in order to reach the necessary escape velocities. (Kass 697) Thus for all the terrestrial planets lighter elements have been continuously lost to space over the lifetime of the planet's atmosphere. This process explains why "only the most massive bodies in the solar system have dense atmospheres, and also that atmospheres are generally depleted in light atoms such as H and He" (Hunten 916) Thus as a result of the mass-selective nature of this process isotope fractionation is predicted. Such fractionation is observed in the atmospheres of the terrestrial planets. (See Table 1) These observed isotope ratios of Ar, C, H and N suggest that a likely loss of 85-95% of each gas. (Brain 22693) The time period over which this loss may have acted is uncertain and it is possible would not have been operative in the past of Mars as a result of a magnetic field. The process of sputtering is active only in the absence of an intrinsic magnetic field for the planet. (Galimov 472) This is because the solar flux provides the energy necessary to drive the process of sputtering. "In the sputtering process, photochemical processes ionize atoms in the upper atmosphere, which are then accelerated due to the magnetic filed in the solar wind." (Brain 22693) In the presence of a magnetic field the solar wind will be diverted around the planet thus the magnetic field in the solar wind won't be able to accelerate particles up to escape velocity. (Hutchins 14939) Evidence for a magnetic field in Mars past can be found in the remnant magnetic field found in ALH80041. (Brain 22693) Although it is possible there was a magnetic field in the Martian geologic past which would have eliminated sputtering as an effective mechanism for atmospheric loss, Kass and Yung found "The closer it is to the present, the weaker are the EUV and solar wind and thus smaller is the precipitating flux" (698) Though the process of sputtering predicts an isotope enrichment the trend we actually observe is more linear than exponential relationship that sputtering predicts as a result of principle term in Jean's escape, $e^{-GMm/Ktr}$ (Hunten 916) .

This linear relationship can be explained by considering an alternative but closely related mechanism of blowoff or hydrodynamic loss. As the lighter atoms, particularly hydrogen, are lost to space they generate an aerodynamic drag. (Hunten 916) The force of this drag will be counterbalanced by the weight force of the atom in question thus resulting in the more linear relationship we observe between mass and volume of gas lost. (917) Hydrodynamic loss is thought to be primarily responsible for the loss of many of the heavier elements to space though it has been demonstrated that collisional sputtering is also capable of removing heavier elements such as the lighter noble gases.(Hutchins 14933) Whether this process is operative or not depends largely on whether the necessary drivers for the system are present. These drivers are large quantities of light gases, most likely hydrogen, and sufficient solar heat deposited high in the atmosphere to drive the flow. (Hunten 917) This mechanism would account for the removal of part of the oxygen that results from the photodissociation of water. (917)

Though sputtering and impact erosion are the two mechanisms most often modeled there are many other complex mechanisms thought to be acting upon the Martian atmosphere. Another such mechanism, the sequestering of the atmosphere by surficial processes is largely used as a means to reconcile the models of other loss mechanisms with current observational evidence. Sequestering of the atmosphere by surficial processes occurs in three ways primarily: adsorption into the regolith, trapping in the polar caps and trapping in subsurface reservoirs. The estimates for how much of the atmospheric constituents are trapped varies widely and is used to account for however much additional carbon dioxide and water were not lost due to the other atmospheric loss mechanisms. Brain and Jakosky suggest 30-40 mbars of carbon dioxide could be adsorbed, as much as 100-200 mbars contained in the polar caps [10 mbar is a more realistic estimate] and an unknown amount of carbonates. (22694) Hunten also suggests the possibility of inconsistencies between his models and observations as a result of adsorbed carbonates and hydrates, reactions with iron in the crust and trapping in the polar caps, though he does not provide estimates for how much carbon dioxide and water is contained in each. (Hunten 919) Lastly, Vlassopoulos predicts the existence of a carbon dioxide liquifer overlying an acquifer which could contain up to 20 bars. (79)

The dynamics of the Martian atmosphere both past and present are quite complex. Our present-day understanding of these dynamics is based on extremely limited data. Though we can model the evolution of the Martian atmosphere relatively well by consideration of the mechanisms discussed in this paper, the requirement of almost all the models for large quantities of atmosphere to have been sequestered in the regolith or in other subsurface reservoirs whose existence and extent is only hypothetical introduces a great deal of uncertainty to these models. In short, though many of the models seem to fairly accurately reflect the evolution of the Martian atmosphere based on our current observational evidence it is impossible to confirm or refute these models until we have a greater wealth of data from Mars.

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