Neon and Argon Isotopic Constraints on Earth-Atmosphere Evolution

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Abstract. The aim of this contribution is to revisit classical Ar-based atmospheric evolution models using constraints derived from non-radiogenic subcomponents (e.g., 20,22Ne and 36,38Ar isotopes) and from radiogenic contributions (e.g., 40Ar) in the main terrestrial reservoirs (excluding the core). The present approach assumes the acquisition of an early atmosphere through, e.g., capture of the solar nebula, impact degassing, fractional escape etc., whose characterization, as far as Ne and Ar are concerned, is constrained using 20Ne/22Ne ratios. These early events were followed by mantle degassing through geological time which is constrained by K-Ar systematics. Ne-Ar isotope considerations allow to predict that the fraction γ of mantle-derived 36Ar in the present-day atmospheric 36Ar is probably lower than 1%. Likewise, the mantle 36Ar/22Ne ratio must be much lower than that of air, and may be solar-like. These predictions are used to constrain a simple model of mantle differentiation where rare gases are extracted together with incompatible elements (e.g., K), but not recycled. Mantle 40Ar/36Ar ratios are in the range 25,000–46,000, and the present-day 36Ar flux from the depleted mantle is compatible within a factor of 2 with that derived from independent flux estimates.

1. Introduction

The formation and evolution of the terrestrial atmosphere has been often modelled using rare gas isotope systematics of terrestrial reservoirs. Most models assume that the present-day atmosphere originated from mantle outgassing, a view somewhat consistent with the behaviour of incompatible elements which were stored in the crust following extraction from the mantle during partial melting. The identification of 40Ar/36Ar isotopes (where terrestrial 40Ar has been completely supplied by the decay of 40K) higher in mantle-derived materials than in air was interpreted as evidence of large-scale fractionation among terrestrial reservoirs with non-radiogenic 36Ar having been extracted from the mantle to the atmosphere. Subsequent mathematical treatment of K-Ar isotope systematics (ALLÈGRE et al., 1986/87; HAMANO and OZIMA, 1978; OZIMA, 1975; SARDA et al., 1985 among others) called for an early catastrophic outgassing event where more than 90% non-
radiogenic Ar was degassed within the first $10^8$ s of yr, followed by residual degassing through volcanism. Such models were corroborated and sharpened using extinct radioactivities of $^{129}$I-$^{129}$Xe and $^{244}$Pu-$^{131-136}$Xe (ALLÈGRE et al., 1986/87; PHINNEY et al., 1978; STAUDACHER and ALLÈGRE, 1982; ZHANG and ZINDLER, 1989).

Independent studies of planetary evolution, mechanisms of accretion and behaviour of primary atmospheres suggested that the above-mentioned view was in fact over-simplified and required additional sources of volatiles and fractionating mechanisms. Among them, hydrodynamic escape of a primary atmosphere and subsequent elemental and isotopic fractionation, impact degassing and heterogeneous accretion (HUN TEN et al., 1987; MARTY, 1989; PEPIN, 1991; SASAKI and NAKASAWA, 1988) have been shown to be able to reproduce some of the characteristics of terrestrial rare gases. In particular, the discovery that the isotopic composition of neon in the mantle is close to the solar composition (HIYAGON et al., 1992; HONDA et al., 1991; MARTY, 1989; SARD A et al., 1988, see Fig. 1) could not be accounted for by realistic isotopic fractionation during magma degassing and required early isolation of surface and mantle Ne reservoirs having distinct isotopic signatures. Although there have been several studies aimed at constraining mantle geodynamics from Ne isotope systematics, the mantle-atmosphere connection in the light of Ne isotope systematics has gained little attention at present. In this paper we present a two-step model for atmospheric evolution which takes into account neon and argon isotopic compositions of the mantle and the atmosphere.

![Diagram](image)

Fig. 1. Three isotope plot for neon (simplified). The MORB and OIB arrays are defined with data from HIYAGON et al. (1992), HONDA et al. (1991) and SARD A et al. (1988). Atmospheric (square), solar (Sucor and solar wind—SW) and planetary (Ne-A) values are from compilation in OZIMA and PODOSEK (1983). "mfl" is the mass fractionation line for non-nucleogenic atmospheric Ne. The "nucleogenic" arrow shows the evolution following nucleogenic production of $^{21}$Ne.
2. The Mixing Hypothesis

It is now clear that the isotopic composition of mantle neon shows excesses in both $^{20}\text{Ne}$ and $^{21}\text{Ne}$ (Fig. 1). Although $^{21}\text{Ne}$ excesses are readily accounted for by nucleogenic production in the Earth through time, $^{20}\text{Ne}$ excesses are best explained by the occurrence of solar Ne in the mantle ($^{20}\text{Ne}/^{22}\text{Ne})_a \sim 13$, compared with an atmospheric ratio of $(^{20}\text{Ne}/^{22}\text{Ne})_a = 9.8$). This observation strongly suggests that the atmosphere does not derive from mantle outgassing through time, but was formed early in the Earth’s history. Atmospheric rare gases could have been contributed following late heterogeneous accretion processes or could have resulted from trapping of a massive steam atmosphere and subsequent gravitational escape and fractionation (e.g., PEPII, 1991, and references therein). These possibilities represent two extreme cases and there is little doubt that both types of processes have contributed to the rare gas elemental and isotopic composition of the atmosphere. In the present work however, no inference on the mechanisms of early atmospheric evolution is made. The processes of isolation of atmospheric and mantle reservoirs must have been rapid since extinct radioactivities have produced distinct patterns in both reservoirs (e.g., ALLEGRE et al., 1986/87; MARTY, 1989; PHINNEY et al., 1978) and, in addition, there is independent evidence from the Precambrian rock record that the atmosphere had already settled down 3.8 Ga ago. Rare gas degassing from the mantle is still active, as evidenced by $^3\text{He}$ excesses in mantle-derived rocks and mid-ocean ridge hydrothermal fluids, which implies that the mantle contributed primordial and radiogenic rare gases during geological time. The atmospheric evolution can therefore be simplified into a two-step process, the first one characterized by a catastrophic evolution and the second one by continuous degassing. The present-day atmospheric composition of Ne—$(^{20}\text{Ne}/^{22}\text{Ne})_a$—therefore results from the addition of solar Ne from the mantle—$(^{20}\text{Ne}/^{22}\text{Ne})_m$—degassed through time, to an initial atmospheric composition—$(^{20}\text{Ne}/^{22}\text{Ne})_i$. The contribution of mantle-derived Ne to atmospheric Ne can be expressed as $\alpha = ^{22}\text{Ne}_m/^{22}\text{Ne}_i$ and the mixing equation can be written as:

$$\alpha = \frac{R_i - R_a}{R_a - R_m}$$  \hspace{1cm} (1)

where $R$ are the $^{20}\text{Ne}/^{22}\text{Ne}$ ratios. Likewise, if $R'$ represents the $^{36}\text{Ar}/^{22}\text{Ne}$ ratio, one gets:

$$\alpha = \frac{R_i' - R_a'}{R_a' - R_m'}$$  \hspace{1cm} (2)

and Eqs. (1) and (2) express $R_i'$ as a function of $R_i$. Thus, regardless of the assumptions made about the origin and process of fractionation of rare gases in the
Fig. 2. Mixing diagram for $^{20}\text{Ne}/^{22}\text{Ne}$ versus $^{36}\text{Ar}/^{22}\text{Ne}$. The mean MORB $^{36}\text{Ar}/^{22}\text{Ne}$ ratio is from SARDA and GRAHAM (1990) and the MORB field for the $^{20}\text{Ne}/^{22}\text{Ne}$ ratio corresponds to the upper limit of MORB values (HIYAGON et al., 1992; SARDA et al., 1988). Mixing between air and solar Ne follows a straight line in this format. The straight line in the right lower part of the diagram represents mixing between a Ne-Ar component in the initial atmosphere and a solar rare gas component deriving from the mantle (see text for further explanations).

initial atmosphere, the mixing hypothesis allows us to infer the path of evolution for the atmosphere through time. The important consequence of this is that the initial $R_i$ and $R_i'$ ratios must have been lower and higher, respectively, than the present-day $R_a$ and $R_a'$ ratios and have been shifted to the present-day value through the addition of mantle-derived gas having higher $R_m$ and lower $R_m'$ ratios.

The evolution trends of $R$ and $R'$ are displayed in Fig. 2, where, given its framework, mixing curves are represented by straight lines. For example, mixing between air and mantle (solar) rare gases is represented by a straight line joining the air and solar poles. The mean MORB $^{36}\text{Ar}/^{22}\text{Ne}$ ratio of 4.3 (SARDA and GRAHAM, 1990) is also indicated, together with the range of the highest $R$ values registered in MORB (HIYAGON et al., 1992; HONDA et al., 1991; SARDA et al., 1988). Both $R_m$ and $R_m'$ ratios are qualitatively consistent with the occurrence of solar-type Ne and Ar in the mantle and satisfy the conditions advocated in the preceding paragraph. In detail however, the mean MORB $^{36}\text{Ar}/^{22}\text{Ne}$ ratio ($R_m'$) appears in excess of the solar $^{36}\text{Ar}/^{22}\text{Ne}$ ratio (0.35, computed with $^{20}\text{Ne}/^{36}\text{Ar} = 37$; ANDERS and GREVESSE, 1989; the choice of the value for the solar component is not critical in the calculation as long as $R_s'$ is small with respect to $R_a'$ or $R_i'$) and may trace moderate atmospheric contamination, as will be discussed later.

3. The Mantle Contribution

The fraction $\gamma$ of $^{36}\text{Ar}$ ($\gamma = [^{36}\text{Ar}]_m/\{[^{36}\text{Ar}]_m + [^{36}\text{Ar}]_i\}$) derived from mantle
outgassing through time in the present-day atmosphere can be expressed as:

$$\gamma = \frac{R_m' (R_i - R_m)}{R_a' (R_i - R_a)}$$

(3)

$R_a$ and $R_a'$ are known from direct measurements of air and $\gamma$ depends on (i) the mantle $^{36}\text{Ar}/^{22}\text{Ne}$ ratio ($R_m'$), and (ii) the $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of the initial atmosphere ($R_i$), two points which merits further discussion.

3.1 The mantle $^{36}\text{Ar}/^{22}\text{Ne}$ ratio

Because the isotopic composition of neon appears solar in the mantle, the mantle $^{36}\text{Ar}/^{22}\text{Ne}$ ratio may be solar as well. Adopting either Solar Energetic Particles (SEP) or solar wind Ar/Ne ratios (values from the compilation in ANDERS and GREVESSE, 1989) leads to similar results for $\gamma$ (Fig. 3), that is, a very small fraction of atmospheric $^{36}\text{Ar}$ is derived from the mantle. For example, $\gamma$ corresponding to the limiting case of $^{20}\text{Ne}/^{22}\text{Ne} = 0$ is 1.41%. However, the MORB $^{36}\text{Ar}/^{22}\text{Ne}$ mean of 4.3 results in much larger $\gamma$ values, with an upper limit of 17.3% for $^{20}\text{Ne}/^{22}\text{Ne} = 0$ (Fig. 3). $^{40}\text{Ar}/^{36}\text{Ar}$ ratios in MORB are known to vary widely and the most probable source of variations is air contamination, as evidenced by the well-

![Graph showing the relationship between $^{20}\text{Ne}/^{22}\text{Ne}$ ratio in the initial atmosphere and the fraction of mantle-derived $^{36}\text{Ar}$ (%).](image)

Fig. 3. $^{20}\text{Ne}/^{22}\text{Ne}$ ratio in the initial atmosphere as a function of the fraction of mantle-derived $^{36}\text{Ar}$ (%) in the present atmosphere. The curves correspond to different $^{36}\text{Ar}/^{22}\text{Ne}$ ratios for the mantle: (1) MORB mean of 4.3; (2) mantle estimate of 2.4, derived from $^{3}\text{He}/^{22}\text{Ne}$ and $^{3}\text{He}/^{36}\text{Ar}$ estimates by O'Nions and Tolstikhin (1994); (3) solar ratio of 0.35, computed for $^{20}\text{Ne}/^{22}\text{Ne} = 13$ with the Ne/Ar ratio given by ANDERS and GREVESSE (1989); (4) SEP ratio with data compiled in ANDERS and GREVESSE (1989), note that in this case the $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of the mantle is not compatible with a SEP origin for Ne.
known $^{40}\text{Ar}/^{36}\text{Ar}$ versus $^{1}/^{36}\text{Ar}$ relationship in MORB (e.g., OZIMA and PODOSEK, 1983). The effect of air contamination is more important in the case of the Ar isotopic ratios than of the Ne isotopic ratios because non-radiogenic Ar is more depleted than Ne in the mantle. In addition, rare gas elemental abundances are subject to elemental fractionation during phase changes and we therefore need an additional criterion in order to select $R_m$. From radiogenic isotope systematics, O’NIONS and TOLSTIKHIN (1994) proposed estimates for the mantle $^{3}\text{He}/^{22}\text{Ne}$ and $^{3}\text{He}/^{36}\text{Ar}$ ratios, which lead to a $^{36}\text{Ar}/^{22}\text{Ne}$ ratio of $2.4 \pm 0.7$. In their approach, non-radiogenic isotope ratios were constrained using radiogenic isotopic ratios which, in the case of Ar, have been chosen to be $\sim 25,000$ for the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio, corresponding to the upper range of MORB values. There is no reason to postulate that the mantle $^{40}\text{Ar}/^{36}\text{Ar}$ ratio is indeed limited to $2-3 \times 10^4$ since the extremely low $^{36}\text{Ar}$ concentration in the mantle source necessary to observe such values is very sensitive to atmospheric contamination, even in marginal proportions. This leaves the possibility that the mantle $^{36}\text{Ar}/^{22}\text{Ne}$ ratio as estimated by O’NIONS and TOLSTIKHIN (1994) may represent an upper limit. These independent approaches show that the mantle $^{36}\text{Ar}/^{22}\text{Ne}$ ratio must be much lower than the air ratio (18.8), probably lower than 2.4 and possibly as low as $\sim 0.35$ (the solar value) when atmospheric contamination is filtered.

3.2 The initial $^{20}\text{Ne}/^{22}\text{Ne}$ ratio ($R_i$)

The $^{20}\text{Ne}/^{22}\text{Ne}$ ratio in the initial atmosphere may have been as low as 0, though this is unlikely. The so-called “planetary” value is about 8.2 (e.g., OZIMA and PODOSEK, 1983), which may represent one possible starting value if the atmosphere was formed following late accretion of a carbonaceous chondrite-type (C1, C3, ...) meteoritic matter, as is often proposed (e.g., DREIBUS and WÄNKE, 1989; JAVOY et al., 1986). Fractionation during hydrodynamic escape also predicts $R_i$ lower than the solar value. OZIMA and ZAHNLE (1993) calculated the decrease of $^{20}\text{Ne}/^{22}\text{Ne}$ and $^{36}\text{Ar}/^{38}\text{Ar}$ as a function of time and, from Fig. 5 in their article, it can be anticipated that the Ne ratio corresponding to an atmospheric $^{36}\text{Ar}/^{38}\text{Ar}$ ratio is $\geq 8$ for reasonable compositions of the steam atmosphere and durations of atmospheric escape. Assuming an initially solar Ne/Ar ratio leads to $\gamma$ between 1.41% for $R_i = 0$ and 0.63% for $R_i = 8$, the latter being close to the so-called “planetary” value, or to the lower limit suggested from the computations of OZIMA and ZAHNLE (1993). The value of $\gamma$ can be further constrained from the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of the mantle, as described in the next section.

4. A Degassing Model for Argon

In this section a simple model for Ar evolution is presented. The radiogenic isotope ($^{40}\text{Ar}$) budget is constrained by that of potassium and the non-radiogenic isotope balance ($^{36}\text{Ar}$) is constrained by the Ne-Ar systematics described earlier.

4.1 Initial conditions

The basic assumptions of the model are:

1. An initial atmosphere was captured following unspecified processes by the terrestrial system, was modified by fractionation or mixing, and “rapidly” ($\sim 10^8$
Table 1: Model parameters, two-box model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
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<tbody>
<tr>
<td>Mass, total mantle</td>
<td>3.75</td>
<td>$10^{27}$ g</td>
</tr>
<tr>
<td>Mass, crust (C) (present)</td>
<td>2.24</td>
<td>$10^{25}$ g</td>
</tr>
<tr>
<td>Mass flux, depleted mantle (DM) to surface</td>
<td>70</td>
<td>$10^{16}$ g/yr</td>
</tr>
<tr>
<td>Mass flux, from DM to undepleted mantle (UM) (present)</td>
<td>4</td>
<td>$10^{16}$ g/yr</td>
</tr>
<tr>
<td>K in the mantle</td>
<td>330</td>
<td>ppm</td>
</tr>
<tr>
<td>$[^{36}\text{Ar}]_{a}$</td>
<td>5.55</td>
<td>$10^{15}$ mol</td>
</tr>
<tr>
<td>$[^{36}\text{Ar}]_{\text{UM}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$[^{40}\text{Ar}/^{36}\text{Ar}]_{a}$ (present)</td>
<td>295.5</td>
<td></td>
</tr>
<tr>
<td>$[^{40}\text{Ar}/^{36}\text{Ar}]_{\text{DM}}$ (present)</td>
<td>$\geq 28,000$</td>
<td></td>
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</tbody>
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- Extraction depth of 60 km under ridges, oceanic crust production of 3 km$^2$/yr. This flux refers to incompatible elements only.
- Mean plume flux from Kellog and Wasserburg (1990)
- 26 ppb U (Jacobsen and Wasserburg, 1979) and K/U = 12,700 (Jochum et al., 1983)
- Ozima and Podosek (1983)
- Depends on $\gamma$
- Highest MORB ratio (Allègre et al., 1986/87 and Sarda and Graham, 1990)
(2) Mantle differentiation took place through time and allowed transfer of Ar to the atmosphere and growth of continental crust with K storage in the crust.

(3) The transfer rates are based on present-day estimates and are assumed to have decreased exponentially through time, as a result of Earth cooling and decreasing radioactivity (Table 1).

(4) Rare gases are outgassed quantitatively from the crystalline upper mantle material to the atmosphere without elemental fractionation. Crystal-melt partition coefficients appear low for He and Ar (Carroll et al., 1994; Marty and Lussiez, 1993), which implies an incompatible behaviour during partial melting. Furthermore, lava degassing under sea-floor conditions appears extremely efficient since only the glassy margins of pillow lavas, a cm or so in thickness, are able to preserve mantle rare gases (Dymond and Hogan, 1973). Consequently, no solubility control on mantle degassing is allowed.

(5) Ar is not recycled into the mantle and Ar is quantitatively degassed from the continental crust. The last assumption is based on the observation of large-scale Ar degassing from the crust with a typical period on the order of ~1 Gyr (Torgersen et al., 1989).

Because the convective regime of the mantle and its possible stratification are still a matter of debate, we have considered two limiting cases for mantle evolution. Either the mantle behaves as a single box during differentiation (single-box model), or crustal extraction preferentially depleted the upper mantle through time (two-box model). In the former, the whole mantle is subject to convection and the degassing

![Cartoon of the two-box model.](image_url)

Fig. 4. Cartoon of the two-box model. The mantle is continuously depleted following extraction of incompatible elements, including rare gases, to the atmosphere and the oceanic (O) and continental (C) crusts. Part of potassium is recycled into the mantle. Argon is degassing from the mantle and from the crust into the atmosphere where it is stored. Ar and K are transported from the undepleted to the depleted mantle through plume diapirs in solid phase. The single-box model is similar except that the mantle has only one mantle box.
flux of a given element is at any time proportional to its mantle concentration. This model includes 4 boxes, the mantle, the oceanic crust, the continental crust and the atmosphere. In the two-box model, the mantle is subdivided into the upper mantle and the lower mantle (Fig. 4). In the two-box model, the mass of the depleted mantle has been taken at 0 at the beginning of the differentiation process and increased through time while the crust formed. Rare gases from the undepleted mantle are transported to the depleted mantle through hot spot diapirs (e.g., KELLOG and WASSERBURG, 1990).

In both cases, the total content of $^{36}\text{Ar}$ in the mantle at the beginning of the process is adjusted to produce the relevant $\gamma$ value (fraction of mantle-derived $^{36}\text{Ar}$ in the present-day atmosphere) constrained earlier.

4.2 Crustal growth
The continental crust is not the major $^{40}\text{Ar}$ contributor to the atmosphere and, as far as Ar isotopes are concerned, its evolution can be viewed as one of simple net accumulation (no continental crust recycling) through time. The rate of continental crust formation approximated by the crustal evolution curves deduced from radiogenic isotope systematics. In the present framework, the crustal growth rate depends on the total convection rate. The latter could have been in the range of 1–6 times the present value (e.g., DES MARAIS, 1985) and recent Nd-Sm isotope modelling suggests that it could have been 10 times faster in the late Archean compared with the present-day mantle (BLICHERT-TOFT and ALBARÈDE, 1994). In the case of the single-box model, a shape which grossly satisfies the current crustal evolution

![Fig. 5. Results of the model showing temporal evolution of the continental crust volume relative to present-day volume. The thick curve refers to the single-box model, with an initial flux rate of 6 times the present-day value. The three thin curves refer to the two-box model with initial flux rates of 3, 6 and 10 times the present-day value.](image)
curves is obtained by assuming that the ancient convection rate was 6 times faster than at present and decreased exponentially to the present-day value (Fig. 5). For the two-box model, a rather good fit is obtained using a factor of 10 decrease. In the following, an initial convection rate 6 times faster than the present-day production rate has been taken. It must be noted that this factor is not critical for the results: for example, choosing a factor of 3 lower would change by 7–8% the atmospheric and mantle $^{40}\text{Ar}/^{36}\text{Ar}$ ratios.

4.3 The two-box model and the evolution of the mantle

If the present-day limit between the depleted and the undepleted mantle is taken to be the 670 km geophysical discontinuity ($M_{UM}/M_{DM} = 2.75$), then a maximum $^{40}\text{Ar}/^{36}\text{Ar}$ value of 150 for atmospheric argon is obtained. This value is rather insensitive to the other parameters because it mainly depends on the initial atmospheric inventory of $^{36}\text{Ar}$ which is close to the present-day $^{36}\text{Ar}$ inventory (the mantle derivation is small for $^{36}\text{Ar}$) and on the K content value adopted for the silicate Earth, which is rather well constrained from U (JACOBSEN and WASSERBURG, 1979, TURCOTTE, 1980) and K/U (JOCHUM et al., 1983) estimates for the silicate Earth. Thus, in order to get an atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ value of 295.5, it is necessary to increase the present-day mass of the depleted mantle and a best fit is obtained for a $M_{UM}/M_{DM}$ ratio of 1.10. The evolution of the 4 solid reservoirs is illustrated in Fig. 6.

![Graph showing reservoir mass evolution over time.](image)

**Fig. 6.** Evolution of the different solid reservoirs of the Earth (excluding the core) through time (two-box model). The flux rates are allowed to decrease from time 0 to the present-day values by a factor of 6 and the fraction $\gamma$ of mantle-derived $^{36}\text{Ar}$ in the atmosphere is fixed at 0.63%. The mass between the undepleted and depleted mantle reservoirs has been adjusted in order to get a $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 300 in the atmosphere.
4.4 Argon in the mantle

The results of interest are the $^{36}\text{Ar}$ contents and the $^{40}\text{Ar}/^{36}\text{Ar}$ ratios in each reservoir. The atmospheric Ar isotopic ratio is used as a constraint to refine the K content of the mantle and partial melting rates. In the case of the single-box model, a bulk partial melting rate of ~3% and an initial K content of the mantle of 220 ppm are necessary to reach a $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 300 in the atmosphere. The corresponding $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of the present-day mantle is found to be 31,857.

In the two-box model, an initial K content of 330 ppm is assumed (Table 1). The parameter to be adjusted is the depth of the depleted/undepleted boundary (see above). The dependence of the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio in the depleted mantle on $\gamma$ is graphically displayed in Fig. 7. For a maximum MORB $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 28,000 (ALLÈGRE et al., 1986/87), a $\gamma$ value of 0.95% is derived. Conversely, for a preferred $\gamma$ value of 0.63% (Section 3), a $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 46,015 is computed. The model is internally consistent, that is, high $^{40}\text{Ar}/^{36}\text{Ar}$ ratios in the depleted mantle require low values of $\gamma$, which are also predicted from independent Ne-Ar isotope systematics (Section 3). The evolution of the $^{40}\text{Ar}/^{36}\text{Ar}$ ratios in the different mantle reservoirs and in the atmosphere is displayed as a function of time in Fig. 8.

The two-box model results in high $^{40}\text{Ar}/^{36}\text{Ar}$ ratios in the undepleted mantle (42,012 for $\gamma = 0.63\%$ and 25,330 for $\gamma = 0.95\%$), a prediction somewhat at odds with the observation of rather low $^{40}\text{Ar}/^{36}\text{Ar}$ ratios in lavas from some hot spots (e.g., ALLÈGRE et al., 1986/87), interpreted either as representative of an undegassed portion of the mantle (e.g., ALLÈGRE et al., 1986/87), or as an effect of atmospheric contamination (e.g., PATERSON et al., 1990). Recent Ar isotopic ratios up to 12,000

![Graph](image.png)

Fig. 7. Dependence of the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio in the depleted mantle with the fraction $\gamma$ of mantle-derived $^{36}\text{Ar}$ in the atmosphere. In order to get $^{40}\text{Ar}/^{36}\text{Ar}$ ratios compatible with values recorded in MORB, it is necessary to have $\gamma \leq 1\%$. 

in Samoan xenoliths showing high $^{3}$He/$^{4}$He ratios (PorEda and Farley, 1992) are suggestive of high Ar ratios even in the less degassed, possibly less depleted, mantle. It is also notable that in the present version of this model, the $^{40}$Ar/$^{36}$Ar ratio of the undepleted mantle (42,012) does not drastically differ from that of the depleted mantle (46,015). The contrast between the 2 reservoirs could be increased by adjusting the transfer rates between the undepleted and depleted mantle, and between the depleted mantle and the surface and/or by allowing recycling of atmospheric argon into the mantle. In this respect, He isotopes will be of great use because, contrary to argon, atmospheric contamination through, e.g., assimilation or recycling, is always very low in the case of helium. A more evolved version of this model, which includes He isotope systematics, is currently in progress.

The present-day $^{36}$Ar concentration of the depleted mantle is computed to be $4.0 \times 10^{-15}$ mol/g for $\gamma = 0.63\%$, which leads to a present-day $^{36}$Ar flux of 2800 mol/yr. On the other hand, the $^{36}$Ar flux as computed from an oceanic $^{3}$He flux of 1100 mol/yr (Craig et al., 1975); a $^{4}$He/$^{40}$Ar production/accumulation rate of 2 and a $^{40}$Ar/$^{36}$Ar ratio of 28,000–46,000 is 1754–1068 mol/yr and therefore agrees within a factor of 2 with the $^{36}$Ar content of the depleted mantle derived from the model.

5. Conclusions

We have attempted to start bridging over the gap separating planetary views of atmospheric evolution and geochemical models based on trace element and radiogenic isotope systematics. The latter envision a progressive fractionation of incompatible elements which are continuously extracted from the mantle to the crust. There is no reason to exclude volatiles, in particular noble gases, from this process, but this view was apparently incompatible with the observation of drastically different rare
gas isotopic ratios in air and in the mantle, which led to the hypothesis of “catastrophic” degassing of the mantle. Ne isotope systematics demonstrate the occurrence an initial atmosphere having a specific rare gas isotopic composition. This initial atmosphere was contributed, marginally in the case of Ar, by mantle outgassing following differentiation through geological time. The present-day isotopic ratios of neon and argon in the atmosphere and in the mantle are consistent with this view, as explained in Section 4 and modelled in Section 5. Both single-box and two-box models for the mantle result in high 40Ar/36Ar ratios in the present-day mantle, with the implication that the matter forming the mantle was thoroughly degassed in rare gases from the beginning, as a possible result of impact accretion.

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