Isotopic Research Related to the Origin of the Solar System

Peter Bochsler

Introduction

Until a decade ago it was generally assumed that the solar system has condensed from a hot, homogeneous nebula. Elemental heterogeneities as found between different classes of meteorites were interpreted as consequences of local elemental fractionation within the nebula following the onset of condensation. Some isotopic heterogeneities in meteorites, such as ^{129}Xe-anomalies originating from the decay of ^{129}I ($T_{1/2} = 15.7 \cdot 10^6$ y), could be explained to be variations in time elapsed between the last nucleosynthetic event and the solidification of the different fragments. All investigations for other isotopic heterogeneities, due to incomplete mixing of the solar nebula, had led to the conclusion, that the solar system material was indeed well mixed at least to the 1‰ level.

In the beginning of the last decade this view of the history of the early solar system was gradually changed: Black (1972) argued that the isotopic pattern of neon as observed in stepwise heating experiments on the Orgueil-meteorite could be due to an admixture of an 'extrasolar component' rich in ^{22}Ne, in the following called 'Neon-E'. Clayton et al. (1973), on the other hand, found that oxygen in meteorites and lunar samples could not simply be explained by fractionation of an originally homogeneous reservoir but rather by fractionation and variable admixture of a component rich in ^{16}O.

In the following Lee et al. (1976) investigated several inclusions in the Allende-meteorite which were considered to be early condensates from the solar nebula and found anomalies of ^{26}Mg correlated with the aluminium content of the samples. They could convincingly interpret this anomaly to be due to 'fossil' ^{26}Al ($T_{1/2} = 0.72 \cdot 10^6$ y) which had been incorporated into their samples before

decay. From this Lee et al. (1977) could conclude that the inclusions of Allende must have been formed only a few million years after a nucleosynthetic event which produced ^{26}Al.

Since 1977 isotopic anomalies have been found in many other chemical elements. More recent reviews have been given by Clayton (1978) and by Wasserburg et al. (1980).

The following short review will be limited to the cases of four elements: Hydrogen, nitrogen, neon, and magnesium. In this context we discuss some consequences of recent discoveries for our understanding of the early history of the solar system.

Deuterium

The solar wind is thought to reflect quite closely isotopic ratios in the outer convective zone of the sun and hence, except for the light elements Li and Be, the composition of the sun at the time of ignition of nuclear burning. Also deuterium does not survive the temperatures at the bottom of the convective zone and is converted to ^{3}He.

From the isotopic ratio ^{3}He/^{4}He in the solar wind as determined with the Apollo foil experiments (Geiss et al., 1972); Geiss and Reeves (1972) could set a firm upper limit to the deuterium content of the primeval sun. The best estimate for the D/H-ratio in the early sun is now $2.0 \cdot 10^{-5}$ (Geiss and Bochsler, 1978). As can be seen from figure 1, the solar value agrees well with the one for interstellar atomic hydrogen (York and Rogerson, 1976 and Vidal-Madjar et al., 1977) and possibly for Jupiter which is controversial (Combes et al., 1978; Trauger et al., 1977). On the other hand, the solar value is well below the terrestrial and the meteoritical values. Special fractions of the Chainpur

DEUTERIUM IN THE SOLAR SYSTEM

METEORITE CHAINPUR

METEORITE RENAZZO (ORGANIC)

CARBON. METEORITES $[CI, CV]$

CARBON. METEORITES $[CM]$

OCEAN WATER

JUPITER

SUN BEFORE D-BURNING

INTERSTELLAR HYDROGEN

10   20   30   40   50   60

$D/H (10^{-5})$
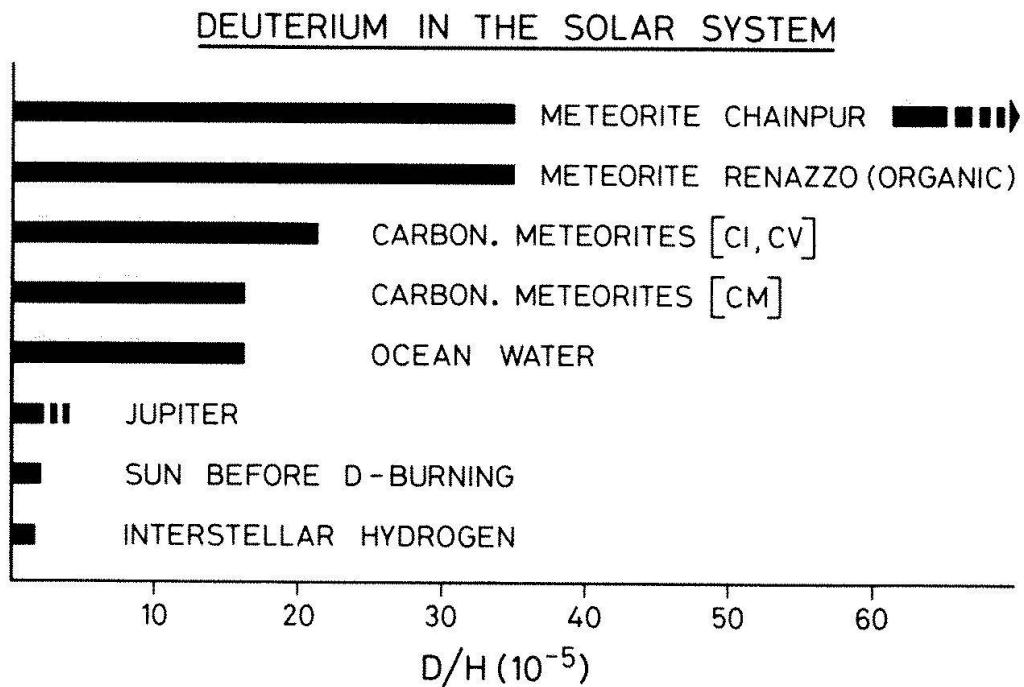
and Renazzo meteorites still show much stronger deuterium enrichments relative to the primordial solar composition (Robert et al., 1979; Kolodny et al., 1980).

The information on the primeval D/H-ratio in the sun is of special importance for modeling the 'big-bang'. It poses limits to the present baryon density ρ_B and hence the deceleration parameter q_0. ρ_B derived from the D/H-value in the early sun and the interstellar gas is compatible with densities derived by other methods, leading to the conclusion that our universe is open.

Geiss and Reeves (1981) have pointed out that the strong enrichment of deuterium relative to normal solar hydrogen as observed in the Chainpur and Renazzo meteorites cannot be due to equilibrium reactions nor to kinetic effects since temperatures below 200 K would have been required to produce such large isotopic shifts. At such low temperatures the equilibrium time would be of the order of 10^{30} years. Geiss and Reeves (1981) therefore suggest that the enrichment has taken place in a similar way as postulated for the strong deuterium enrichments observed in molecular clouds, i.e. via ion-molecule reactions which would proceed at a sufficiently fast rate. It is not clear whether the presence of strong D-enrichments in the organic fractions of carbonaceous meteorites and also in terrestrial hydrogen excludes the possibility that all

solar system material had been heated to temperatures above 2000 K, disrupting existing molecules, previous to formation of the planetary bodies. This conclusion will arise later from different observations; however, as indicated in the introduction, the formation of the solar system most probably was completed within a few million years while the lifetime of molecules in clouds might be of the order of 10^7 years, which would leave some more time for D-enrichment. At present it looks more likely that the organic matter in Chainpur and Renazzo has survived the process of formation of the solar system and is a witness of the existence of the presolar molecular cloud.

Nitrogen

In the previous section we have shown that deuterium anomalies in the solar system are entirely due to chemical and not to nuclear effects.

In a recent paper (Geiss and Bochsler, 1982) we have investigated evidence for the presence of an anomaly in the isotopic composition of nitrogen in different planetary bodies and the sun. Our motivation for this study was the ongoing discussion on the question whether the isotopic composition of nitrogen at the solar surface has changed by 30% during the history of the sun or not: Kerridge

(1975) discovered a strong anticorrelation of the $^{15}N/^{14}N$-ratio in surface implanted nitrogen in lunar soil with the cosmic-ray produced ^{21}Ne in the soil. It was already known before, that most of this surface implanted nitrogen (as an element) must be due to the solar wind. Clearly the observed anticorrelation of ^{15}N with ^{21}Ne could not be the consequence of spallation produced ^{15}N in lunar soil since then one would rather expect a correlation. Kerridge (1975) explained this correlation as evidence for a secular increase of the $^{15}N/^{14}N$-ratio in the solar wind by approximately 30% during the last $4 \cdot 10^9$ years. Becker and Clayton (1975) suggested another explanation for the apparent secular change in the isotopic composition of surface implanted nitrogen: They attributed the secular change to a varying admixture of a second component with a low $^{15}N/^{14}N$-ratio which was emanating from the lunar interior. However no trace of such a component in lunar rocks was found and this hypothesis was abandoned. Despite the difficulty to explain a secular increase of the $^{15}N/^{14}N$-ratio in the outer convective zone of the sun by nuclear reactions at the solar surface this remained the most favoured hypothesis.

In our paper (Geiss and Bochsler, 1982) we have reassessed the evidence against nuclear production of ^{15}N and destruction of ^{14}N at the solar surface and provided several further arguments against it. We conclude that the apparent secular trend in the isotopic composition of nitrogen trapped in lunar soils must be due to an admixture of a component of light nitrogen ($\delta^{15}N \lesssim -400\permil$)*) from a source with decreasing yield during the age of the regolith. Evidence for such a component is found in some meteorites: If one assumes the hypothesis of a secular increase at the solar surface to be true, one is led to the conclusion that solar nitrogen, and hence the bulk of the solar system nitrogen consists of a light isotopic mixture. According to our explanation however, bulk solar system nitrogen is a heavy isotopic mixture. This idea is support-

ed by the fact that the class of meteorites which is least depleted in volatiles, the carbonaceous chondrites of class 1, contain heavy nitrogen ($\delta^{15}N \cong +40\permil$). Meteorites depleted in volatiles tend towards lighter nitrogen. It appears that the postulated anomalous light component is ubiquitous in the solar system and could possibly also be used to explain the difference between the nitrogen composition of the sun and the terrestrial atmosphere. Principally it is possible, that the anomalous light component could have been depleted in ^{14}N by kinetic effects from an originally heavier component. In our paper we favour the idea that this light component stems from a different nucleosynthetic process and was incorporated into refractory phases.

Neon

When Black and Pepin (1969) investigated neon in carbonaceous meteorites by the stepwise heating technique they found that always one component released at $1000\,°C$ was enriched in ^{22}Ne relative to ^{20}Ne and other temperature steps by factors up to 3. Black (1972) postulated that an extrasolar component – in the following called 'Neon-E' – must be present in carbonaceous meteorites. This hypothetical component should be rich in ^{22}Ne and it should be concentrated in a special mineral phase which releases neon at about $1000\,°C$. Eberhardt (1974) succeeded to isolate a Ne-E rich carrier phase from the Orgueil carbonaceous meteorite. Since then, the upper limits for ^{20}Ne- and ^{21}Ne-contents of Ne-E have been steadily lowered by further improvement of the experimental techniques. This is illustrated in a logarithmic three-isotope plot (figure 2) taken from Jungck and Eberhardt (1979). From this diagram it is evident that a component consisting essentially of pure ($>99\%$) ^{22}Ne must be present in Orgueil. Eberhardt et al. (1979a,b) have shown that there are at least two carriers for Ne-E. This is shown in fig. 3 taken from Eberhardt et al. (1979b): The first carrier has a density of less than $2.3\ g/cm^3$. It releases Ne-E at temperatures below $900\,°C$ and is poor in target elements for cosmogenic ($=$ cosmic ray produced) neon such as Mg, Al, and Si, as can

---

*) We here use the 'delta-notation':

$$\delta^{15}N_{sample} = \frac{(^{15}N/^{14}N)_{sample} - (^{15}N/^{14}N)_{air}}{(^{15}N/^{14}N)_{air}} * 1000\permil$$
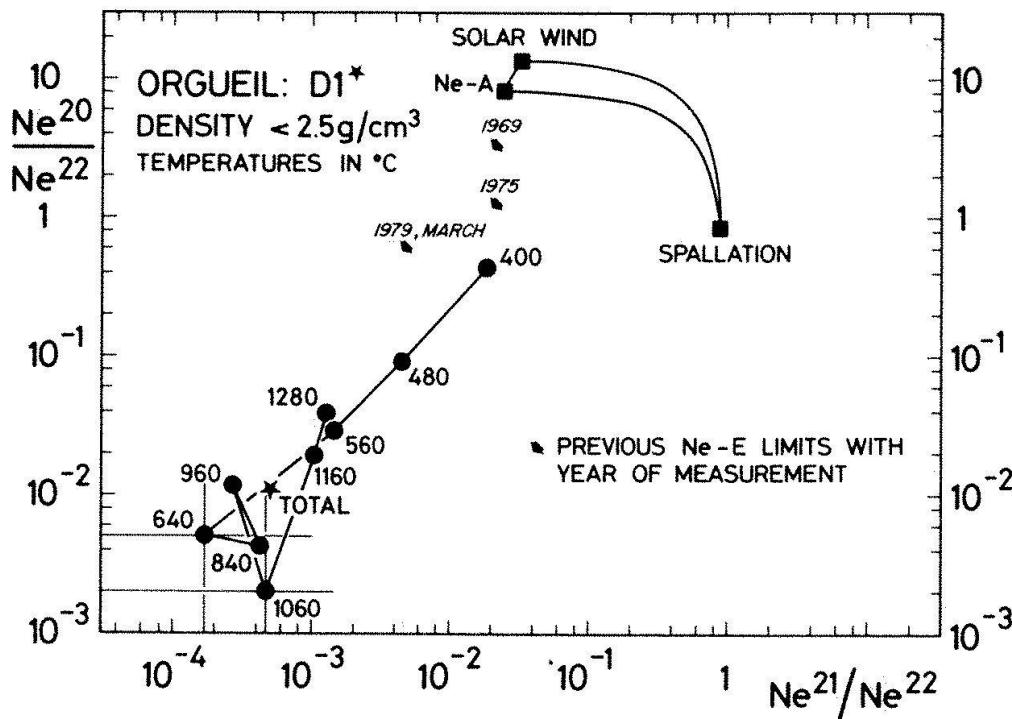
Fig. 2.
Neon three isotope diagram with the results of stepwise heating experiment on the Ne-E rich phase D1* separated from the C1 chondrite Orgueil.
(From Jungck and Eberhardt 1979)
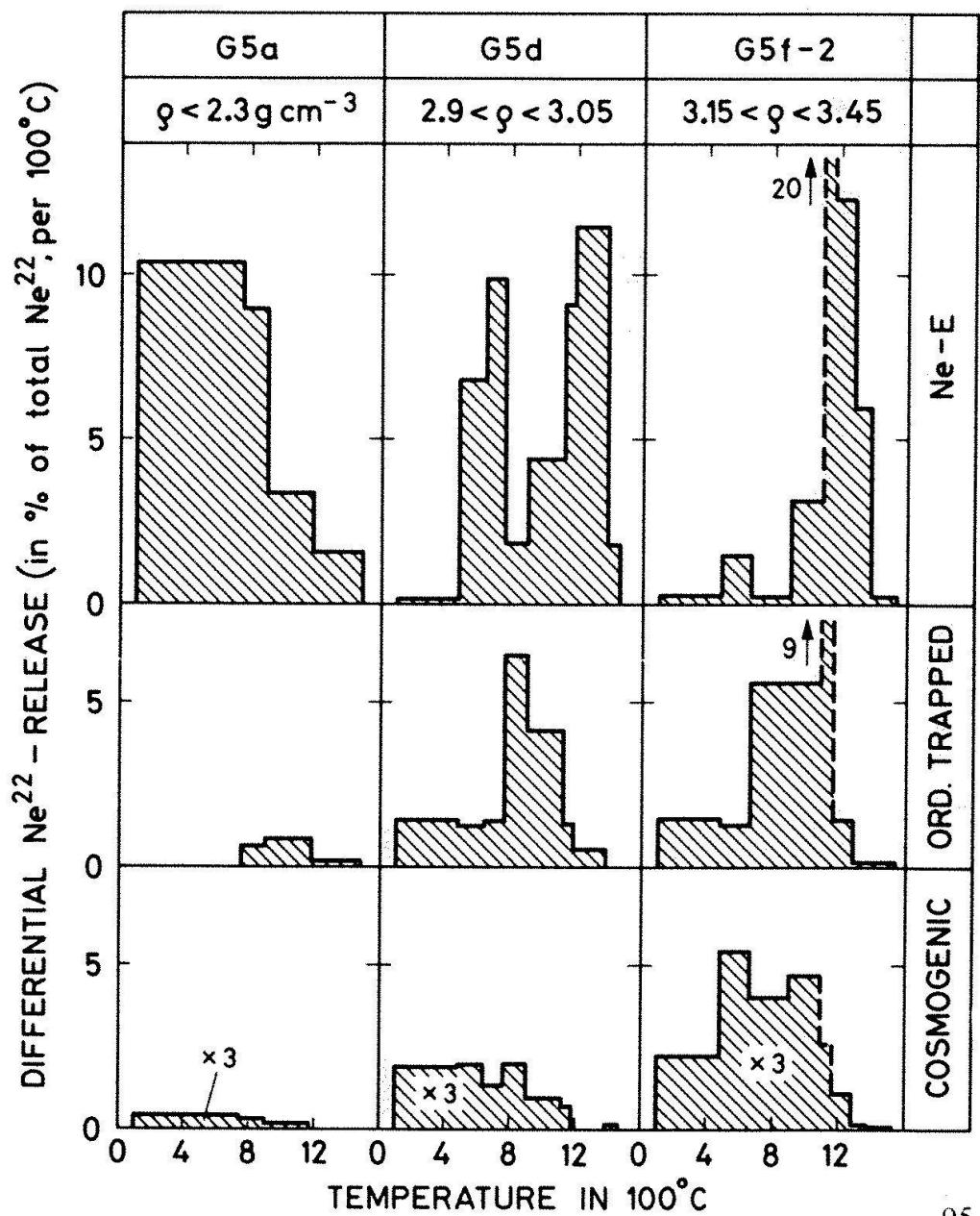
Fig. 3.
Differential gas release observed for three density separates from Orgueil. Shown are the absolute amounts of gas released per °C of temperature increase, and the areas in the histograms correspond to the gas concentrations.
(From Eberhardt et al. 1979a)
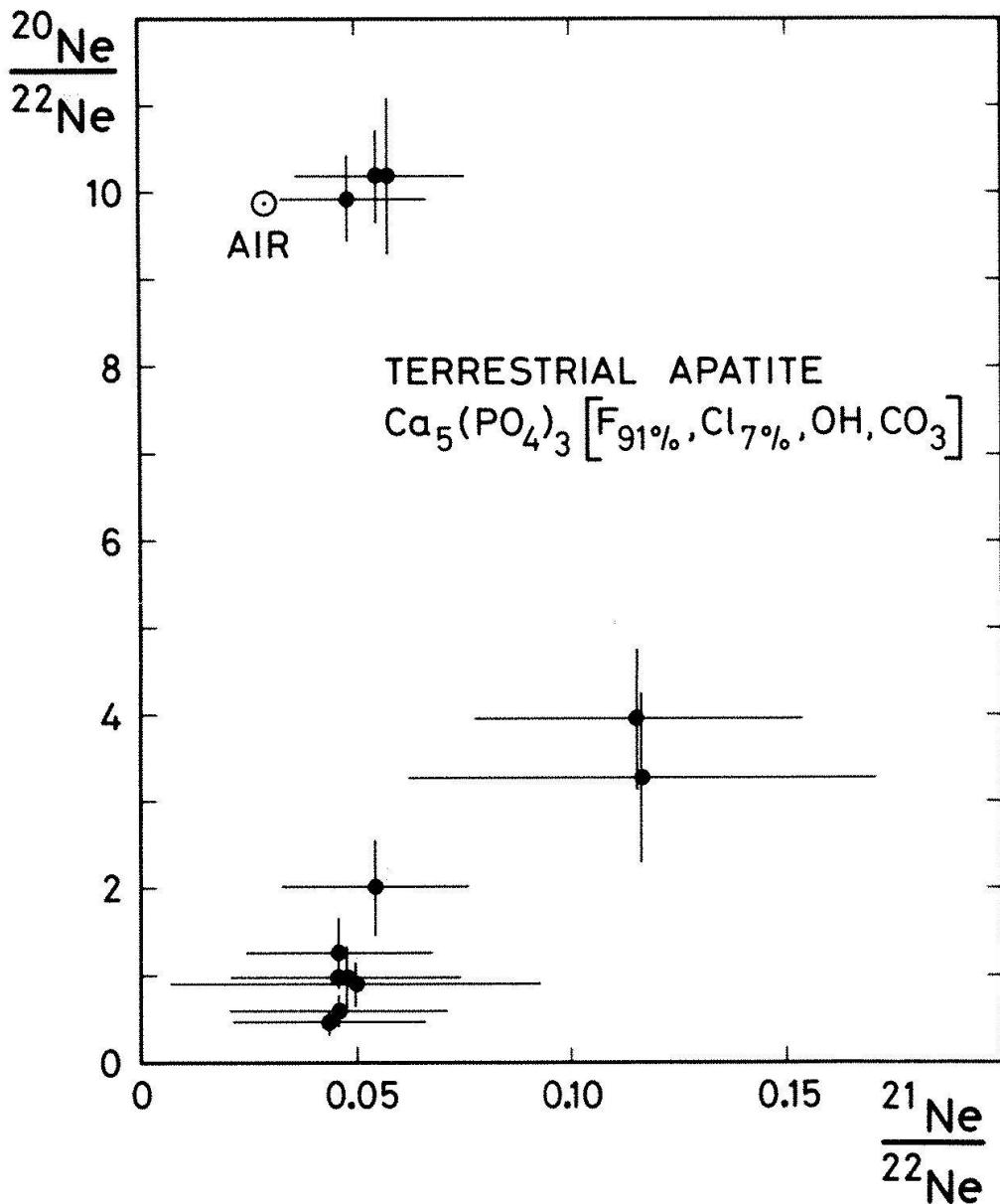
Fig. 4.
Neon three isotope diagram with results of stepwise heating experiment on a terrestrial fluorapatite.
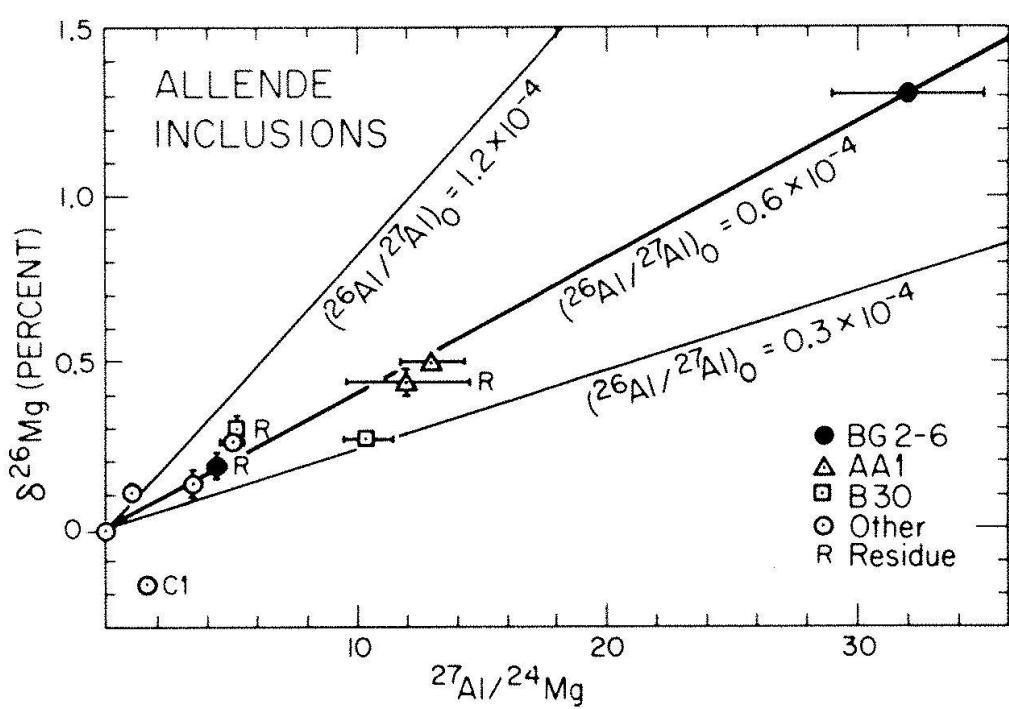
Fig. 5.
Al-Mg evolution diagram for Allende samples. The correlation line for BG2–6 yields $(^{26}Al/^{27}Al)_0 = 6 \times 10^{-5}$ and contrasts sharply with the correlation line for B30 which has essentially zero slope and much higher initial $^{26}Mg/^{24}Mg$.
(From Lee et al. 1976)

be derived from the low concentration of spallogenic ^{21}Ne. The second carrier has a density between 3.15 and 3.45 g/cm^3. It releases Ne-E at temperatures above 900 °C and must contain some target elements for cosmogenic Ne. More recently Jungck et al. (1981) have provided strong evidence that the heavier carrier is, or must be closely attached to apatite. The fraction G5f-2 also contains some olivine which could provide the target elements for cosmogenic neon as visible in figure 3 (Eberhardt et al., 1981).

Origin of Neon-E

Clearly, ^{22}Ne in such a degree of purity as obtained by Jungck and Eberhardt (1979) cannot be produced by fractionation of solar neon: If we assume Rayleigh distillation with a fractionation factor of $(1 - \sqrt{m_{20}/m_{22}})$ this would require a depletion of neon by a factor 10^{-65} in order to obtain the necessary concentration of ^{22}Ne. The incorporation of Ne-E into the samples is still not understood, particularly the fact that apatite might be one of the carriers is puzzling: As Eberhardt et al. (1981) point out, ^{22}Ne can be produced by reactions of α-particles with ^{19}F. Unfortunately the cross section for this reaction is not known. By the stepwise heating technique we have investigated neon in an almost pure fluorapatite which contained approximately 3.4 weight percent F. The sample investigated contained a sizeable amount of Th and U which produced a large concentration of ^{4}He. The neon data plotted in a conventional three-isotope plot (Fig. 5) indicate the presence of three components: The first component, being essentially atmospheric neon with ^{20}Ne/^{22}Ne = 10 is released at temperatures below 600 °C. The second component is enriched in ^{22}Ne and contains also some ^{21}Ne. The third is enriched in ^{21}Ne and ^{22}Ne. The first component can be interpreted as atmospheric neon in small inclusions or dissolved in the crystal lattice, the second component is probably the result of the reactions of α-particles from the U/Th-decay with fluorapatite. The third might be due to irradiation of a second unidentified mineral with a lower F/O-ratio than in fluorapatite present in the sample. From our measurement we can derive a production ratio for ^{21}Ne/

^{22}Ne in fluorapatite of 0.030. Related to the abundances of ^{18}O and ^{19}F this would give a cross section ratio (integrated over the spectrum of α-particles from U/Th-decay) of 1.5 close to the value of 1, assumed by Eberhardt et al. (1981).

Since the ^{19}F(α,n)^{22}Na reaction has a higher coulomb-barrier and a higher threshold energy than ^{18}O(α,n)^{21}Ne, assuming a steeper energy spectrum of α-particles would even increase the ^{21}Ne/^{22}Ne-production ratio. Thus we are probably on safe ground if we conclude that Ne-E in apatite was not produced by irradiation of this mineral with energetic α-particles. There are two more arguments against this: As Eberhardt et al. (1981) point out, no evidence for excess ^{4}He is found in their samples. In addition, in any astrophysical environment which generates energetic α-particles one would also expect a certain amount of energetic protons. This would then produce spallogenic argon from calcium. In G5f Eberhardt et al. (1981) find only $1.2 \cdot 10^{-8}$ cm^3 spallogenic ^{38}Ar. If G5f is essentially apatite, this amount could be produced within 10^6 years by irradiation with galactic cosmic rays (Bochsler et al., 1969). This has to be compared with the exposure age of 10^7 y determined by Jeffery and Anders (1970). Obviously there is no room for additional irradiation. Therefore Eberhardt et al. (1981) conclude, that Ne-E was most likely incorporated in interstellar grains in the form of ^{22}Na. Since ^{22}Na has a half-life of only 2.6 years this incorporation must have taken place very soon after production of ^{22}Na.

Extinct Al-26

Schramm et al. (1970) have investigated several feldspar samples of meteorites, in which extinct ^{129}I ($T_{1/2} = 15.7 \cdot 10^6$ y) had been found before, for extinct ^{26}Al ($T_{1/2} = 0.72 \cdot 10^6$ y). No trace of this isotope was found and the authors concluded that ^{26}Al could not have been important as heat source in parent bodies of meteorites at the time of solidification of feldspar. After the discovery of anomalous oxygen in carbonaceous chondrites by Clayton et al. (1973) and after the finding of minerals considered to be 'high temperature condensates' in the Allende meteorite it

appeared to be worthwhile to investigate these minerals for extinct ^{26}Al, despite the previous experience with other meteorites. Subsequently Lee et al. (1976) discovered a strong correlation of excessive ^{26}Mg with the Al/Mg ratio in several inclusions. It was obvious at once that not all inclusions fell on the same isochrone as can be seen in figure 5 which is taken from Lee et al. (1976). In the following, Lee et al. (1978) could show that in one single chondrule from Allende, coexisting mineral phases provided an isochrone with an initial ^{26}Al/^{27}Al-ratio of $(5.1 \pm 0.6) \cdot 10^{-5}$. Lee et al. (1978) could therefore exclude the possibility that the isochrone was the result of a mixture of two phases with different amounts of inherited ^{26}Mg excess and came to the conclusion that ^{26}Al must have decayed in situ. It should be mentioned however, that not all early condensates of Allende contain fossil ^{26}Al. Lee et al. (1979) discovered a hibonite inclusion ($CaAl_{12}O_{19}$) with Ca-anomalies but no trace of extinct ^{26}Al. The authors point out that the question of the relation of ^{26}Al with other nuclear anomalies is still open.

Nevertheless two conclusions can be drawn: ^{26}Al can again be considered as an important potential heat source for planetary bodies. Secondly, the formation of the solar system must probably have started within a few million years after the last nucleosynthetic event.

Conclusions

The observations by Lee et al. (1976, 1978), that the formation of the solar system took place only within a few million years after the last nucleosynthetic event, strongly supports present ideas on the close relation of nucleosynthesis and star formation. It is now generally accepted, that stars form within clusters. An initial trigger for the onset of star formation in a dense molecular cloud might be the passage through a galactic spiral density wave. Massive stars can contribute in two ways to the sequence of the following events: First, by formation of HII-regions and possibly by supernova explosions they can fragment the molecular cloud in which they have been formed (Silk, 1979) and hence propagate star formation. Second-

ly: Supernovae explosions inject freshly synthesized material into the protostellar gas. Such a last injection might have also contained ^{26}Al, although ^{26}Al could as well have been produced in a red giant (Nørgaard, 1980). Another piece of evidence for the close relation of star formation and nucleosynthesis has been given by Reeves and Johns (1976) who showed that nucleosynthesis occurs in bursts which can be correlated to the passage of galactic spiral density waves through the galactic medium.

The survival of some volatile anomalies such as Ne-E requires that the anomaly-bearing grains have not been heated to temperatures above 1200 K. Thus we should expect that these grains, after their formation, could not have been exposed to strong heating of nearby massive stars or near supernovae explosions. We expect that the life expectancy of a dust grain in the environment of star formation can only be rather short so that only a very limited number of nucleosynthetic sources for Ne-E can be involved. It could therefore well be that in our view the importance of nucleosynthesis of refractory anomalies such as ^{26}Al, in the era shortly before formation of the solar system is exaggerated due to the preferred survival of anomalies in refractory elements.

Theory of star formation shows that the presence of dust grains in collapsing molecular clouds is important, since grains are the most efficient cooling agent at temperatures of a few hundred K, thus keeping the collapse going on. The presence of volatile anomalies shows that grains indeed have been around during star formation and could even survive the initial stages of star birth.

The presence of ^{26}Al is of enormous importance for heat generation within planetesimal bodies. As Lee et al. (1977) have pointed out, as soon as bodies of a few 100 km are formed, the heat generated by the decay of ^{26}Al can bring temperatures in the interior of such a body to several thousand degrees. This might cause disruption of smaller bodies or segregation of different phases in larger bodies where the interior gravitational field is sufficiently strong to keep viscous melts moving.

Unsegregated large bodies can only form if they incorporate little or no ^{26}Al, i.e. if they

form practically without Al (and other refractory elements) or late (10^7 to 10^8 y after synthesis of ^{26}Al).

Many questions remain unsettled, one of the most intriguing problems is the lack of correlation between many anomalies. It appears that e.g. the neon anomaly is decoupled from all the other anomalies except maybe xenon and krypton. On the other hand there is a clear clustering of anomalies in refractory elements in some inclusions of the Allende meteorite. As pointed out earlier, the distribution of anomalies is not uniform in these inclusions. It appears that the early solar system was chemically and isotopically heterogeneous and contained many distinct reservoirs which themselves result from incomplete mixing of different nucleosynthetic products. Clearly, the field of nuclear and chemical anomalies in the solar system will continue to evolve rapidly in the next years, some of the questions raised will be solved, many new questions will be open.

Acknowledgements

Abstract

A decade ago it was generally accepted that the solar system has condensed from a chemically homogeneous cloud and that the cloud material has been heated to temperatures above 2000 K shortly before the formation of the bodies of the solar system. Recent investigations in the field of isotopic research have demonstrated that this picture no longer holds: Many chemical elements in planetary bodies contain isotopic anomalies, showing that matter has not been completely homogenized previous to formation of the solar system. In the case of some elements we show some implications of the recent discoveries on our understanding of the early history of the solar system.

References

Becker, R.H., and R.N. Clayton, Nitrogen abundances and isotopic compositions in lunar samples. Proc. Lunar Sci. Conf. 6th (1975) 2131–2149.

Black, D.C., On the origins of trapped helium, neon and argon isotopic variations in meteorites-II. Carbonaceous meteorites. Geochim. Cosmochim. Acta 36 (1972) 377–394.

Black, D.C., and R.O. Pepin, Trapped neon in meteorites-II. Earth Planet. Sci. Lett. 6 (1969) 395–405.

Bochsler, P., P. Eberhardt, J. Geiss, and N. Grögler, Rare gas measurements in separate mineral phases of the Otis and Elenovka chondrites. In Meteorite Research, D. Reidel Publishing Company, Dordrecht, Holland (1969) 857–874.

Clayton, R.N., Isotopic anomalies in the early solar system. Ann. Rev. Nucl. Part. Sci. 28 (1978) 501–522.

Clayton, R.N., L. Grossman, T.K. Mayeda, A component of primitive nuclear composition in carbonaceous meteorites. Science 182 (1973) 485–488.

Combes, M., T. Encrenaz, and T. Owen, On the abundance of deuterium in Jupiters atmosphere. Astrophys. J. 221 (1978) 378–381.

Eberhardt, P., A neon-E rich phase in the Orgueil carbonaceous chondrite. Earth Planet. Sci. Lett. 24 (1974) 182–187.

Eberhardt, P., M.H.A. Jungck, F.O. Meier, and F. Niederer, Neon-E. New limits for isotopic composition. Two host phases? Lunar and Planet. Sci. 10 (1979a) 341–343.

Eberhardt, P., M.H.A. Jungck, F.O. Meier, and F. Niederer, Presolar grains in Orgueil: Evidence from Neon-E. Astrophys. J. 234 (1979b) L169–L171.

Eberhardt, P., M.H.A. Jungck, F.O. Meier, and F.R. Niederer, A Neon-E rich phase in Orgueil: Results obtained on density separates. Geochim. Cosmochim. Acta 45 (1981) 1515–1528.

Geiss, J., and H. Reeves, Cosmic and solar system abundances of Deuterium and Helium-3. Astron. Astrophys. 18 (1972) 126–132.

Geiss, J. and P. Bochsler, On the abundances of rare ions in the solar wind. Proc. 4th Solar Wind Conf., Burghausen (1978).

Geiss, J. and P. Bochsler, Nitrogen isotopes in the solar system. Geochim. Cosmochim. Acta 46 (1982) 529–548.

Geiss, J. and H. Reeves, Deuterium in the solar system, Astron. Astrophys. 93 (1981) 189–199.

Geiss, J., F. Bühler, H. Cerutti, P. Eberhardt, and Ch. Filleux, Solar wind composition experiment, Apollo 16 Prelim. Sci. Rep. NASA SP-315 (1972).

Jeffery, P.M. and E. Anders, Primordial noble gases in separated meteoritic minerals. Geochim. Cosmochim. Acta 34 (1970) 1175–1198.

Jungck, M.H.A. and P. Eberhardt, Neon-E in Orgueil density separates, Meteoritics 14 (1979) 439–441.

Jungck, M.H.A., F.O. Meier, and P. Eberhardt, Apatite in Orgueil carrier phase for Neon-E? Meteoritics 16 (1981) 336–337.

Kerridge, J.F., Solar nitrogen: Evidence for a secular increase in the ratio of nitrogen 15 to nitrogen 14. Science 188 (1975) 162.

Kolodny, Y., J.F. Kerridge, and I.R. Kaplan, Deuterium in carbonaceous chondrites. Earth Planet. Sci. Lett. 46 (1980) 149–158.

Lee, T., D.A. Papanastassiou, and G.J. Wasserburg, Demonstration of ^{26}Mg excess in Allende and evidence for ^{26}Al. Geophys. Res. Lett. 3 (1976) 41–44.

Lee, T., D.A. Papanastassiou, and G.J. Wasserburg, Aluminium-26 in the early solar system: Fossil or Fuel? Astrophys. J. 211 (1977) L107–L111.

Lee, T., W.A. Russell, and G.J. Wasserburg, Calcium isotopic anomalies and the lack of aluminum-26 in an unusual Allende inclusion. Astrophys. J. 228 (1979) L93–L98.

Norgaard, H., ^{26}Al from red giants. Astrophys. J. 236 (1980) 895–898.

Reeves, H., and O. Johns, The long live radioisotopes as monitors of stellar, galactic and cosmological phenomena. Astrophys. J. 206 (1976) 958.

Robert, F., L. Merlivat, and M. Javoy, Deuterium concentration in the early solar system: Hydrogen and oxygen isotope study. Nature 282 (1979) 785–789.

Schramm, D.N., F. Tera, and G.J. Wasserburg, The isotopic abundance of ^{26}Mg and limits on ^{26}Al in the early solar system. Earth Planet. Sci. Lett. 10 (1970) 44–59.

Silk, J., Molecular clouds and star formation. In: 10th Advanced Course of the Swiss Society of Astronomy and Astrophysics (1980) A. Maeder and L. Martinet, editors.

Trauger, J.T., F.L. Roesler, and M.E. Mickelson, The D/H ratios on Jupiter, Saturn und Uranus based on new HD and H_2 data. Bull. Amer. Astron. Soc. 9 (1977) 516.

Vidal-Madjar, A., C. Laurent, R.M. Bonnet, D.G. York, The ratio of deuterium to hydrogen in interstellar space III. The lines of sight to Zeta Puppis and Gamma Cassiopeiae, Astrophys. J. 211 (1977) 91.

Wasserburg, G.J., D.A. Papanastassiou, and T. Lee, Isotopic heterogeneities in the solar system. In: Early Solar System Processes and the Present Solar System (D. Lal, editor) North Holland Publishing Company, Amsterdam (1980).

York, D.G., and J.B. Rogerson, The abundance of deuterium relative to hydrogen in interstellar space. Astrophys. J. 203 (1976) 378.

Address of the author:

Dr. Peter Bochsler
Physikalisches Institut der
Universität Bern
Sidlerstrasse 5
CH-3012 Bern (Schweiz)