Chapter 6

Summary and Conclusions

The primary aim of this thesis was to analyze pristine CAIs from primitive meteorites to understand the formation and evolution of these early solar system objects and to delineate the time scales of early solar system processes. CAIs from the carbonaceous chondrite Efremovka, representing different petrographic types, that have not undergone major secondary alteration, were selected for this study. These CAIs have been analyzed for their Mg, K and Ca isotope compositions. In addition, several CAIs from the Grosnaja meteorite with distinct signatures of secondary petrographic alterations were also analyzed to assess the effect of secondary alterations on Mg-Al isotopic systematics. The isotopic studies were carried out using the techniques of secondary ion mass spectrometry. A brief summary of the work carried out and the important results and conclusions obtained are given below.

The Efremovka CAIs studied in this work encompass all the major petrographic types (A, B1, B2 and hibonite-rich) which allow us to generalize upon our results. Since these studies were carried out on a newly acquired ion microprobe, the instrument was thoroughly tested for its suitability for high mass resolution isotopic studies of Mg, K, Ca and Ti by analyzing terrestrial analogs of the meteoritic phases. Extensive tests were carried out to ensure that conditions necessary for reproducible and high-precision isotopic measurements are adequately met by the instrument. Measurement of terrestrial standards as well as isotopically doped silicate glasses gave good results with a precision of 2‰($2\sigma_m$) for magnesium isotopic analysis even on samples with low Mg content (few hundred ppm). Reliable measurements of isotopic compositions of other elements (e.g. Ca and Ti) that require extremely high mass resolution ($M/\Delta M \sim 10{,}000$) could also be performed with high precision.

Magnesium isotopic studies of Efremovka CAIs belonging to different petrographic types revealed well-behaved isotopic systematics. This confirms their pristine nature as inferred from earlier trace element as well as petrographic studies which showed the near absence of secondary alteration products in these inclusions. The isotopic data provided new information on the nebular sites and processes responsible for the formation of the CAIs, and also on the distribution of ^{26}Al in the solar nebula. These are:

(i) Sympathetic behaviour of isotopic and petrographic data, seen for the first time in a non-FUN refractory inclusion (E40), substantiates the role of volatilization as an important CAI forming process. A short duration volatilization event, affecting the parent melt of this CAI, can best explain the observed correlation between isotopic and petrographic data in this Efremovka CAI.

(ii) The presence of relict spinel was inferred from the observed isotopic disequilibrium in coexisting spinel and melilite in an once-molten Efremovka CAI. This facilitates finer constraints on the cooling rate of the parent melt of this inclusion. The deduced cooling rates range from few degrees to few hundred degrees per hour depending on the initial temperature of the source melt (1400 to 1500°C). Such cooling rates are not viable in the low pressure nebular environment. Further, the predicted temperatures of < 1000°K in the meteorite forming zone (~ 3AU), in the standard model of solar nebula, point towards localized hot and dense regions, that allow for both partial melting of refractory precursors of CAIs and appropriate cooling rate, as the most plausible site for CAI formation. This also suggests an efficient gas-dust fractionation mechanism operating in the nebula.

(iii) All the Efremovka CAIs and one of the Grosnaja CAIs are characterized by the presence of excess ^{26}Mg which correlates well with ^{27}Al, confirming the presence of live ^{26}Al in the nebula at the time of formation of these CAIs. The values for the initial aluminium and magnesium isotopic ratios at the time of formation of the different Efremovka CAIs can be explained if we consider a relatively uniform source reservoir characterized by a normal magnesium isotopic composition and an initial ^{26}Al/^{27}Al close to the canonical value of 5×10^{-5}. The disturbed isotopic systematics, seen in one of the Efremovka CAIs, can be understood in terms of partial reequilibration involving isotopic exchange between two mineral phases with contrasting Al/Mg ratios. The observed extreme variation in initial ^{26}Al/^{27}Al in the Grosnaja CAIs can be attributed to post-formation processes affecting these CAIs. Our data, therefore, suggest a relatively homogeneous distribution of ^{26}Al in the region of CAI formation. We do not favour the view of an extremely heterogeneous distribution of ^{26}Al in the solar nebula, proposed to explain the large variation ^{26}Al/^{27}Al seen in many CAIs. As most of these CAIs also show clear signatures of secondary alteration, these variations most probably reflect late stage disturbances in Mg isotopic systematics due to secondary processes affecting these CAIs. If we consider all the isotopic data in totality it is however difficult to rule out the presence of more than one distinct reservoir of ^{26}Al in the solar nebula.

(iv) The K-Ca isotopic studies of Efremovka CAIs have indicated definite presence of ^{41}K excess in them which correlates well with ^{40}Ca content of the analyzed phases. Several possibilities like neutron induced reaction during cosmic ray exposure of the Efremovka meteorite, contribution from 'fossil' ^{41}K locked in stellar condensates that can find their way into the CAIs, and the presence of 'live' ^{41}Ca in the early solar system were considered. The last alternative can best explain our observations. Our data yield an initial ^{41}Ca/^{40}Ca ratio of $(1.6 \pm 0.3) \times 10^{-8}$ at the time of formation of Efremovka CAIs. ^{41}Ca can now be added to the list of extinct radionuclides that were present in the early solar system.

(v) The presence of short-lived radionuclides ^{26}Al and ^{41}Ca allows us to put strong constraint on the time interval between the cessation of nucleosynthetic input to the solar nebula and the formation of solar system objects. Our data suggest this time interval to be < 1Ma. Such a short time interval is also consistent with the recent observation of excess ^{60}Ni (resulting from decay of ^{60}Fe [meanlife $\sim$ 2Ma]) in differentiated meteorites that suggests the formation of large ($\gg$ Km -sized) objects in the early solar system and their subsequent melting, cooling and recrystallization within a short span of < 10Ma.

6.1 Scope for Future Work

The work presented in this thesis represents the first detailed study of pristine CAIs from the Efremovka carbonaceous chondrite. The study was conducted to explore the possibility of a better understanding of the processes in the formative stages of the solar system. The Efremovka CAIs have lived up to the promise of their primeval nature. The results summarized in the preceding pages are very encouraging and attest to the utility of carrying out detailed study of such CAIs.

The petrographic and isotopic studies of Efremovka CAIs have allowed us to identify important CAI forming process like volatilization. Similar studies of CAIs from the carbonaceous chondrites Vigarano and Leoville that are also free from major secondary alteration effects will be useful in this regard. Laboratory based simulation experiments have indicated the formation of Ca-aluminates during intense evaporation of melilite. Such phases are not present in any of Efremovka CAIs analyzed in this work although they are present in some other Efremovka CAIs (e.g., E66). Detailed studies of such CAIs may further improve our understanding and quantification of processes like volatilization during the formation of CAIs.

The advantages of isotopic studies in identifying relict phases have been clearly demonstrated in this study. Relict grains can probably go a long way in indentifying precursors of not only CAIs but also of chondrules. In fact a very recent report on observation of relict spinel in chondrules (Misawa and Fujita 1994) suggests CAIs as one of the precursor component of chondrules. The constraints on nebular environment for CAI formation, obtained from this study, should be cross checked by studying other CAIs. These may provide us with finer details of nebular environment (e.g. extent of gas-dust fractionation, temperature and density) which can improve our understanding of the state of the solar nebula. The nature and cause for the localized heat source is not well understood and needs further study.

Mg-Al isotopic systematics of Efremovka CAIs negate the idea of an extremely heterogeneous distribution of ^{26}Al in the solar nebula. Although the sample set consisted of the major petrographic types, type C and fine-grained inclusions did not form a part of this study. Isotopic studies of such inclusions from other meteorites are few in number. A study of petrographically unaltered type C and fine-grained inclusions from Efremovka will probably complete the picture. Further studies of CAIs from CV and CM meteorites may probably allow us to identify if there were more than one distinct reservoir of ^{26}Al and their spatial extent. Proper identification of the causes for the presence of distinct reservoirs of ^{26}Al will enhance our understanding of mixing scale lengths of dust and gas in the evolutionary epoch of the solar nebula or vice versa.

The story of ^{41}Ca has just begun, and it is necessary to study a large number of CAIs to establish its presence on a firm footing. The important Ca-rich phases e.g. hibonite and perovskite, which are less abundant in CAIs from CV meteorites but more abundant in CM meteorites, could not be studied in detail in this work. These phases are probably better candidates than pyroxenes for such studies. Enstatite chondrites which have formed in a reducing environment have an important phase, oldhamite (CaS), this may also be suitable for K-Ca isotopic studies.

The list of possible short-lived radionuclides whose presence in the early solar system has been established is far from complete. Although the presence of ^{60}Fe has been established in differentiated meteorites, its presence in CAIs or chondrules is yet to be confirmed experimentally due to the lack of Fe-rich Ni-poor phases in these objects. If the secondary alteration processes affecting the CAIs took place rather early in the history of the solar system the Fe-rich altered phases in CAIs (e.g. hedenbergite, garnet, hercynite) may be good candidates for such studies. In addition, one can also analyze Fe-rich olivine grains in chondrules. Presence of ^{99}Tc ($t_{1/2} \sim 0.2$Ma) and ^{36}Cl ($t_{1/2} \sim 0.3$Ma) which decay to ^{99}Ru and ^{36}Ar respectively, is yet to be conclusively established. A hint for the presence of ^{99}Tc in the early solar system was reported by Yin et al. (1992) in the Marlinga meteorite. Since ^{99}Tc and ^{36}Cl have halflives more than twice that of ^{41}Ca they should have been present in the early solar system at the time of CAI formation. The presence of ^{99}Tc in AGB stars undergoing thermal pulsations is well established. Therefore, excess ^{99}Ru due to ^{99}Tc decay in primitive objects will provide strong experimental evidence in favour of the recent proposal that a single AGB star was a major contributor of several short-lived radionuclides to the solar nebula (Wasserburg et al., 1994). Further, it would be interesting to investigate the production rates of ^{41}Ca and ^{36}Cl in AGB stars. Another important question is whether the contribution of short-lived radionuclides to the solar nebula was from a single source or multiple sources over a long period of time. The currently available data on ^{26}Al and ^{60}Fe favour a single injection (Wasserburg et al. 1994). Presence of ^{41}Ca, and ^{99}Tc and ^{36}Cl (if proven) will provide rigorous constraint in this regard. While both thermal ionization mass spectrometer and ion microprobe will play significant role in our future endeavour to understand the formation and early evolution of the solar system, higher resolution ion microprobe than presently available will probably be best suited for further studies of refractory microphases from primitive meteorites.