The evolution of the solar system started with the gravitational collapse of a dense interstellar molecular cloud about 4.6 billion years ago that led to the formation of the proto-Sun at the center, surrounded by a rotating cloud of gas and dust, the so called solar nebula. The solar nebula is expected to be extremely hot initially due to the very high activity of the proto-Sun that released tremendous amount of energy into its surroundings. This is also corroborated by the presence of rare refractory objects in chondritic meteorites, termed Ca-Al-rich Inclusions (CAIs), that are considered to be the first solids to form in the solar nebula. Many of the CAIs have characteristics that suggest them to be direct nebular condensates, while others have undergone episodes of melting and recrystallization at high temperature (MacPherson et al., 2003). Chondrules, small (0.1 to a few mm-sized) spheroidal silicate objects, that are abundant in chondritic meteorites are considered to be products of high temperature transient events in the solar nebula that led to melting of pre-existing solids followed by rapid cooling resulting in their formation. In comparison to the CAIs, that are mostly present in the carbonaceous chondrites, chondrules are ubiquitous in all chondritic meteorites and constitute up to 80% by volume in unequilibrated
ordinary chondrites (UOCs). Formation of chondrules thus represents a major event in the early history of the solar system. However, several important questions such as the textural and chronological relations between CAIs and chondrules, the time and duration over which chondrule formation persisted in the solar nebula and the exact mode of formation of chondrules, particularly the source of transient heating event, are not well understood at present. Understanding the processes and timescales of chondrule formation, and its relation to CAIs can significantly advance our understanding of the solar nebula processes.

Efforts have been made by several groups to understand the time and duration of chondrule formation using the now-extinct short-lived radionuclide $^{26}$Al (half life=0.72 Ma) as a chronometer. $^{26}$Al decays to $^{26}$Mg and the former presence of $^{26}$Al in early solar system objects (e.g. CAIs) is inferred from observed excess in the abundance of $^{26}$Mg in them (Lee et al., 1976, 1977). It may be noted that the inferred chronological information is valid only if we assume that these objects formed in a reservoir in which $^{26}$Al was homogeneously distributed with a well defined initial $^{26}$Al/$^{26}$Al ratio that decreased with time owing to decay of $^{26}$Al. A detail analysis of $^{26}$Al records in CAIs as well as time-scales inferred from studies of $^{26}$Al and other now-extinct short-lived radionuclides in early solar system objects support this assumption (MacPherson et al., 1995; Halliday and Kleine, 2006; Thrane et al., 2006).

The initial Al-Mg isotope studies of meteoritic chondrules were conducted in Al-rich chondrules that contain phases with high Al/Mg ratios suitable for such a study. Most of the chondrules, however, are ferromagnesian in nature and the rare Al-rich chondrules may not be representative of chondrules in general. Several studies of ferromagnesian UOC chondrules have been carried out and at present the duration of formation of chondrules inferred from these studies varies from ~1 Ma to 4 Ma (Russell et al., 1996; Kita et al., 2000, 2005a; Huss et al., 2001; Mostefaoui et al., 2002). A time interval of 1 - 2 Ma has also been suggested
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between formation of CAIs and UOC chondrules. Similar inferences have also been drawn from studies of plagioclase-rich chondrules in carbonaceous chondrites (Sheng et al., 1991; Hutcheon and Jones, 1995; Krot et al., 1999; Srinivasan et al., 2000; Hutcheon et al., 2000; Marhas et al., 2000; Amelin et al., 2002; Kunihiro et al., 2004; Kurahashi et al., 2004). The choice of appropriate meteorite samples for the study of Al-Mg isotope systematics in chondrule is also important. It is now well established that $^{26}$Al was a major heat source in the early solar system (Urey, 1955; Srinivasan et al., 1999). $^{26}$Al along with the now-extinct radionuclide $^{60}$Fe (half life=1.5 Ma; Shukolyukov and Lugmair, 1993; Tachibana and Huss, 2003; Mostefaoui et al., 2005; Tachibana et al., 2006) are considered as responsible for early melting of planetesimals as well as thermal metamorphism in meteorite parent bodies. The possibility of thermal metamorphism affecting the Al-Mg isotope systematics in chondrules from different UOCs that have experienced a range of thermal histories, cannot be ruled out. In general, UOCs of low petrologic grades that have undergone low degree of thermal metamorphism are considered to be suitable sample for such a study. In this study, I have carried out petrographic and Al-Mg isotope studies of a set of chondrules from nine UOCs of low petrologic grades to enhance our understanding of the time of onset and duration of chondrules formation in the early solar system. The possibility of thermal metamorphism in chondrules from UOCs belonging to low petrologic grades is also examined. Data obtained in this study are combined with the existing Al-Mg isotope data for CAIs and chondrules to infer the life time of an active solar nebula during which CAIs and chondrules have formed. In this chapter, I briefly describe the now-extinct short-lived radionuclides present in the early solar system, the nature of the early formed solar system objects, the use of $^{26}$Al to obtain chronological information, the present status of studies related to chronology of chondrule formation and the role of $^{26}$Al as a heat source during the early evolution of the planetesimal. Finally, I present a summary of the main objectives of this thesis work.
1.1 Short-lived radionuclides in the early solar system

The presence of the now-extinct short-lived radionuclides in early solar system objects plays an important role in our understanding of the origin and early evolution of the solar system. The discovery of $^{129}$Xe excess in Richardton meteorite in 1960 (Jeffery and Reynold, 1961) was ascribed to the presence of the short-lived radionuclide $^{129}$I (half life=15.7Ma) in the early solar system that was incorporated "live" into this meteorite and decayed in-situ resulting in the observed excess of $^{129}$Xe. Since then, studies of meteorites have provided evidence for the presence of several other now-extinct radionuclides, such as $^{41}$Ca, $^{36}$Cl, $^{26}$Al, $^{60}$Fe, $^{10}$Be, $^{53}$Mn, $^{107}$Pd, $^{182}$Hf, $^{129}$I, $^{92}$Nb, $^{244}$Pu, $^{146}$Sm in the early solar system. Although the presence of these nuclides is inferred from the observed excess in their daughter products (e.g. $^{26}$Mg in case of $^{26}$Al, $^{41}$K in case of $^{41}$Ca, $^{60}$Ni in case of $^{60}$Fe, $^{10}$B in case of $^{10}$Be, etc), a proof for in-situ decay of these nuclides in the analyzed samples comes from the demonstration of a correlation of the excess with the abundance of the stable parent elements (e.g. a correlation of excess in $^{26}$Mg/$^{24}$Mg with $^{27}$Al/$^{24}$Mg). The half lives of these nuclides vary from 10$^5$ yrs to 10$^8$ yrs and are listed in Table 1.1.

The preservation of evidence for prior existence of any now-extinct radionuclide requires that the analyzed sample behaved as a close system from the time when these nuclides were still extant and got incorporated into the sample. Study of short-lived radionuclide helps in constraining the time-scales and processes that have shaped the early evolution of the solar system. They serve as excellent time markers with high precision of less than a million year (Ma) for events that occurred 4.6 billion years ago and over timescales of a few Ma to a few tens of Ma. Absolute chronology based on long-lived radionuclides as chronometer cannot provide the precision needed to resolve such time difference, except in U-Pb dating in very favourable cases. Of course unlike the long-lived radionuclides, that provide abso-
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lute chronology, the short-lived now-extinct radionuclides can only provide relative chronology between events marking various episodes in the early solar system.

Several sources have been suggested for the presence of the short-lived radionuclides in the early solar system. Irradiation of gas and dust in the solar nebula by energetic particles from an active early sun as well as a stellar source injecting freshly synthesized short-lived radionuclides into the collapsing proto-solar cloud.

Table 1.1: Short-lived radionuclides in early solar system

<table>
<thead>
<tr>
<th>Short-lived Radionuclide</th>
<th>Half life (Ma)</th>
<th>Daughter nuclides</th>
<th>Initial abundance* (ref. nuclide)</th>
<th>Analyzed objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{41}$Ca</td>
<td>0.1</td>
<td>$^{41}$K</td>
<td>$(1.5 \times 10^{-8})$ $^{40}$Ca$^1$</td>
<td>CAIs</td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>0.3</td>
<td>$^{36}$Ar</td>
<td>$(1.5 \times 10^{-6})$ $^{35}$Cl$^2$</td>
<td>CAIs, Chondrules</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>0.72</td>
<td>$^{26}$Mg</td>
<td>$(5 \times 10^{-5})$ $^{27}$Al$^3$</td>
<td>CAIs, Chondrules, Achondrites</td>
</tr>
<tr>
<td>$^{60}$Fe</td>
<td>1.5</td>
<td>$^{60}$Ni</td>
<td>$(~0.2-1) \times 10^{-6})$ $^{56}$Fe$^4$</td>
<td>Chondrules, Chondrites, Achondrites</td>
</tr>
<tr>
<td>$^{10}$Be</td>
<td>1.5</td>
<td>$^{10}$B</td>
<td>$(~1 \times 10^{-4})$ $^{9}$Be$^5$</td>
<td>CAIs</td>
</tr>
<tr>
<td>$^{53}$Mn</td>
<td>3.7</td>
<td>$^{53}$Cr</td>
<td>$(~1.4-4 \times 10^{-5})$ $^{55}$Mn$^6$</td>
<td>CAIs, Chondrules, Achondrites</td>
</tr>
<tr>
<td>$^{107}$Pd</td>
<td>6.5</td>
<td>$^{107}$Ag</td>
<td>$(~4.5 \times 10^{-5})$ $^{108}$Pd$^7$</td>
<td>Iron meteorites, Pall-asites</td>
</tr>
<tr>
<td>$^{182}$Hf</td>
<td>9</td>
<td>$^{182}$W</td>
<td>$(10^{-4})$ $^{180}$Hf$^8$</td>
<td>Achondrites</td>
</tr>
<tr>
<td>$^{129}$I</td>
<td>15.7</td>
<td>$^{129}$Xe</td>
<td>$(10^{-4})$ $^{127}$I$^9$</td>
<td>Chondrules, Chondrites</td>
</tr>
<tr>
<td>$^{92}$Nb</td>
<td>36</td>
<td>$^{92}$Zr</td>
<td>$(10^{-4})$ $^{93}$Nb$^{10}$</td>
<td>Chondrites, Mesosiderites</td>
</tr>
<tr>
<td>$^{244}$Pu</td>
<td>82</td>
<td>Fission</td>
<td>$(7 \times 10^{-3})$ $^{238}$U$^{11}$</td>
<td>CAIs, Chondrites</td>
</tr>
<tr>
<td>$^{146}$Sm</td>
<td>103</td>
<td>$^{142}$Nd</td>
<td>$(9 \times 10^{-4})$ $^{147}$Sm$^{12}$</td>
<td>Chondrites</td>
</tr>
</tbody>
</table>

* w.r.t. reference nuclide (e.g. $^{40}$Ca in case of $^{41}$Ca)

$^1$Srinivasan et al., 1994, 1996; $^2$Murty et al., 1997; Lin et al., 2005; $^3$Lee et al., 1976, 1977; $^4$Shukolyukov and Lugmair, 1993; Tachibana and Huss, 2003; Mostefaoui et al., 2005; $^5$Mckeeegan et al., 2000a; $^6$Brick and Allègre, 1985; Lugmair and Shukolyukov, 1998; $^7$Chen and Wasserburg, 1990; $^8$Kleine et al., 2002; Yin et al., 2002; $^9$Jeffery and Reynold, 1961; $^{10}$Harper, 1996; Schönbächler et al., 2002; $^{11}$Hudson et al., 1988; $^{12}$Lugmair et al., 1983.
have been proposed. If we consider a stellar source and assume a homogenous
distribution of the injected short-lived radionuclides in the nebular region where
formation of objects such as CAIs, chondrules and differentiated meteorites are tak­
ing place, the observed initial abundances of these nuclides provide relative time
scales of formation of these objects. On the contrary, the records of solar energetic
particle interactions with nebular material will depend upon the activity of the sun
as well as other parameters, such as effective irradiation time and irradiation geome­
try, and cannot be used for inferring relative timescales of early solar system objects.
However, such records will help us to understand the energetic environment in the
nebula during the early evolution of the sun and the solar system.

1.2 THE FIRST SOLAR SYSTEM OBJECTS

Thermodynamical, petrological, chemical and isotopic studies of meteorite samples
suggest that the following three groups of objects represent primary early solar
system objects known to us at present. They are (i) Refractory objects such as corun­
dum, hibonite and CAIs with fractionated unidentified nuclear anomalies (FUN),
(ii) normal CAIs and (iii) chondrules. These objects are considered as products of
high temperature nebular processes. Recent studies suggest that some of the sec­
ondary (differentiated) objects such as achondrites may have also formed very early
in the solar system (Bizzarro et al., 2005a).

1.2.1 CORUNDUM, HIBONITE AND FUN CAIs

Corundum, hibonite and FUN CAIs, found primarily in carbonaceous chondrites,
are rare and characterized by large stable isotope anomalies such as enrichment in
neutron rich isotopes, $^{48}$Ca and $^{50}$Ti (Fahey et al., 1987; Ireland, 1990; Marhas et al.,
2001) and/or highly fractionated isotopic composition (Clayton and Mayeda, 1977;
Wasserburg et al., 1977; Davis et al., 1991). If we consider an initially hot nebula ($T >$
2000 °C) of solar composition and a pressure of $10^{-3} - 10^{-4}$ torr, thermodynamical calculations suggest that corundum and hibonite are the first condensates to form in the solar system (Grossman, 1972). Apart from large stable isotopic anomalies these objects are also characterized by enhanced rare earth and refractory trace element abundances following certain patterns. Even though these objects are considered to be the first solids to form in the solar system, they are devoid of or had extremely low abundance of the now-extinct nuclides, such as $^{26}$Al and $^{41}$Ca, at the time of their formation. Several explanations have been put forward, and it appears feasible that formation of these objects may have taken place before the injection of the short-lived radionuclides from a stellar source into the solar nebula (Sahijpal and Goswami, 1998). Another possibility is that $^{26}$Al was heterogeneous distributed in the solar nebula and these objects formed in a nebular region devoid of $^{26}$Al (MacPherson et al., 1995).

1.2.2 Normal CAIs

CAIs are generally found in carbonaceous chondrites and are rare in ordinary or enstatite chondrites. Nonetheless, CAIs constitute a small but important component of chondritic meteorites. Chemical and isotopic properties of CAIs suggest that they are among the most primitive and oldest objects in the solar system having a Pb-Pb age of 4567.2 ± 0.6 Ma (Amelin et al., 2002). CAIs have also preserved fossil records of short-lived radionuclides, such as $^{26}$Al, $^{41}$Ca and $^{10}$Be. CAIs have liquidus temperature of about 1700 K and isotopic and petrographic studies suggest cooling rates of 2 – 50 °C/hr. Many CAIs appear to have undergone partial melting and have slower cooling rates compared to chondrules. Fossil records of now-extinct short-lived radionuclide $^{26}$Al have been extensively studied in CAIs and led to the suggestion for a canonical initial solar system $^{26}$Al/$^{27}$Al ratio of $5 \times 10^{-5}$ (MacPherson et al., 1995). However, lower initial $^{26}$Al/$^{27}$Al ratios are also seen in some CAIs. Petrographic studies of such CAIs suggest that they have experienced secondary
disturbances that most probably perturbed the Al-Mg isotope system leading to 
the lower initial values. The initial $^{26}\text{Al}/^{27}\text{Al}$ ratios in CAIs range from $4 \times 10^{-5}$ and 
$5 \times 10^{-5}$; this spread, if converted into time gives a duration of CAIs formation of 
$\sim 0.2$ Ma (MacPherson et al., 1995), although this variation may reflect analytical 
uncertainty as well. A recent study of high precision Al-Mg isotope systematics 
in CAIs from Allende meteorites suggests an even shorter time of $\sim 30,000$ years as 
the duration of CAI formation (Bizzarro et al., 2004). There are recent suggestions 
that the initial $^{26}\text{Al}/^{27}\text{Al}$ may be higher by a few tens of percent from the presently 
accepted value of $5 \times 10^{-5}$ (Bizzarro et al., 2004, 2005b; Young et al., 2005); however, 
in this study the value of $5 \times 10^{-5}$ is adopted for interpreting the data.

1.2.3 CHONDRULES

Chondrules, the most abundant constituent of chondritic meteorites, are small sili­
cate dominated spheroids formed via melting of solid precursors followed by fast 
cooling. Formation of chondrules was a major event in the early history of the solar 
system and an understanding of the chondrule formation process and its duration 
is of important significance. Chondrules from all chondrite groups show a wide 
range in size from a few tens of microns to a centimeter. However, a vast majority 
of them have a mean diameter of $\sim 1$ mm. Chondrules also show a wide diversity 
in physical and chemical properties, mineralogy, textural type and are usually com­
posed of silicate minerals such as olivine, pyroxene, rare plagioclase, glass, troilite, 
Fe-Ni metal, etc. Even though Al-rich phases are rare in ferromagnesian chondrules 
from UOCs, successful attempts have been made to analyze Al-Mg isotope system­
atics in such chondrules. These studies reveal a range in the initial $^{26}\text{Al}/^{27}\text{Al}$ ratio 
in UOC chondrules at the time of their formation, these values are much lower 
than the value of $5 \times 10^{-5}$ commonly seen in CAIs. This difference suggests that CAI 
formation preceded chondrule formation by at least a million year (Russell et al., 
1996; Kita et al., 2000; Srinivasan et al., 2000; Huss et al., 2001; Mostefaoui et al.,
Introduction

2002). Lead-lead ages of chondrules in the carbonaceous (CR) chondrite Acfer 059 and CAIs from the (CV) chondrite Efremovka also suggest an interval of 2.5 ± 1.2 Ma between formation of the CV CAIs and the CR chondrules (Amelin et al., 2002).

Chondrules have been heated to their liquidus temperature which varies enormously with their bulk compositions. For porphyritic chondrules, the temperature experienced is considered to be little below liquidus that permitted survival of seed nuclei for the generation of crystalline texture on cooling. The melting time, originally postulated to have lasted for several hours, is now considered to be less than a few minutes to take into account retention of moderately volatile elements such as Na and S. Peak temperature inferred from comparison of laboratory simulation experiments with chondrule textures suggest a range of 1800 K to 2200 K. Cooling rates of chondrules are much faster than CAIs and estimates of linear cooling rates vary from 50 to 1000 °C/hr (Hewins et al., 1996; Jones et al., 2000). Several heating mechanisms for chondrule formation have been proposed. Although none of the models is in conformity with all the observed petrographical and chemical properties of chondrules, at present shock induced heating appears to be a plausible mechanism of chondrules formation (Connolly and Love, 1998; Desch and Connolly, 2002; Desch et al., 2005). The most widely studied chondrules are ferromagnesian i.e. Fe, Mg-rich chondrules. The present study focuses on determining the time of onset and duration of chondrule formation in the solar nebula from a study of Al-Mg isotope systematics in chondrules from various UOCs of low petrologic grade. The time starting with the formation of CAIs and the completion of chondrule formation also provide an estimate of the lifetime of the dynamically active phase of the solar nebula when these two objects formed in high temperature events in the nebula. This time scale is an important parameter that needs to be accommodated in any realistic model of the early evolution of the solar system. In this study, I have carried out Al-Mg isotopic analysis of a set of UOC chondrules. The analyzed UOCs belong to petrologic grade 3 and have experienced relatively low degree of thermal
processing in their parent bodies. The petrologic grade 3 is further sub-divided into 10 classes from 3.0 to 3.9 using various indicators of thermal metamorphism such as TL sensitivity, presence of presolar grains (diamonds), degree of heterogeneity in olivine, amount of primordial $^{36}$Ar, degree of matrix recrystallization, Cr distribution in olivine, etc (Sears et al., 1980; Huss et al., 1995, 2006). The maximum temperature experienced by UOCs belonging to different petrologic grades have been inferred by using various metamorphic indicators and these data suggest that chondrules from UOCs belonging to petrologic grades 3.0 to 3.4 are useful for conducting Al-Mg isotope studies. UOCs belonging to petrologic grade 3.0 are expected to experience temperatures not more than 250 °C, while those belonging to 3.4 did not experience temperature greater than 450 °C in their parent bodies (Sears et al., 1991; Huss et al., 2006). Laboratory experiments show that such temperatures, even if they lasted for tens of million years, will not lead to Mg diffusion that may affect the Al-Mg isotope systematics in Al-rich phases like plagioclase (LaTourrette and Wasserburg, 1998). Based on previous studies reported in literature, I have included in our study chondrules from nine UOCs belonging to petrologic grade 3.0 to 3.3 for studying their Al-Mg isotope systematics. It should be noted that there is no evidence of excess $^{26}$Mg due to decay of $^{26}$Al in chondrules from UOC belonging to petrologic grade greater than 3.4, indicating that they are prone to possible thermal disturbance affecting their Al-Mg isotope records (Huss et al., 2001).

1.3 $^{26}$Al as a Chronometer

The present work involves study of Al-Mg isotope systematics and the use of the short-lived radionuclide $^{26}$Al (half life=0.72 Ma), that decays to $^{26}$Mg, as a chronometer for inferring the time scale of formation of chondrules relative to CAIs. The discovery of $^{26}$Mg excess due to decay of $^{26}$Al in Allende CAIs (Lee et al., 1976, 1977) established that CAIs have incorporated live $^{26}$Al at the time of their formation that
decayed in-situ to $^{26}\text{Mg}$. In practice, one measures the Al and Mg isotope ratios and a plot of measured $^{26}\text{Mg}/^{24}\text{Mg}$ versus $^{27}\text{Al}/^{24}\text{Mg}$ should define a correlation line often called as "isochron", if $^{26}\text{Al}$ decayed in-situ and the Al-Mg isotope system is well behaved. The slope of this isochron yields the initial $^{26}\text{Al}/^{27}\text{Al}$ ratio in the object at the time of its formation. If the initial $^{26}\text{Al}/^{27}\text{Al}$ ratio differs for any two analyzed early solar system objects, then this difference, coupled with the half life of $^{26}\text{Al}$, allow us to find the time difference between their formation. Implicit here is the assumption of a homogeneous initial $^{26}\text{Al}$ reservoir in the solar nebula where the formation of early solar system objects such as the CAIs and chondrules took place, and a closed system behavior of Al-Mg isotope system in them. Objects with high initial $^{26}\text{Al}/^{27}\text{Al}$ ratio (higher slope) represent early formed objects and those with lower ratio (lower slope) indicate late forming objects (Figure 1.1). Since the CAIs have a well defined initial $^{26}\text{Al}/^{27}\text{Al}$ of $5 \times 10^{-5}$, a determination of initial $^{26}\text{Al}/^{27}\text{Al}$ ratios of chondrules will provide their time of formation relative to the CAIs. A spread in the initial $^{26}\text{Al}/^{27}\text{Al}$, if observed amongst the chondrules, will provide the duration over which chondrules formation was taking place in the nebula. As noted earlier (section 1.1) we also assume a stellar origin of $^{26}\text{Al}$ that was injected into the protosolar cloud and got homogenized within the nebula. A stellar origin for $^{26}\text{Al}$ as well several other short-lived radionuclides is supported by several observations that include initial solar system abundances of $^{26}\text{Al}$ and $^{41}\text{Ca}$ ($t_{1/2}=0.1$ Ma) in CAIs from the CV (Vigarano-like) and CM (Murchison-like) carbonaceous chondrites (Sahijpal et al., 1998, 2000), unequivocal detection of $^{60}\text{Fe}$ (half life=1.5Ma; Tachibana et al., 2003; Mostefaoui et al., 2005) that is a product of stellar nucleosynthesis and whose initial abundance ($^{56}\text{Fe}/^{60}\text{Fe} > 10^{-7}$) rules out energetic particle production (Goswami et al., 2005). Even though the possibility of an inhomogeneous distribution of $^{26}\text{Al}$ is still being debated, the canonical value of initial $^{26}\text{Al}/^{27}\text{Al}$ present in most of the petrographically undisturbed CAIs (MacPherson et al., 1995) and the close agreement of the inferred time scales for various events in the early solar system based
Figure 1.1: Example plot of $^{26}\text{Mg}/^{24}\text{Mg}$ vs. $^{27}\text{Al}/^{24}\text{Mg}$ expected for different objects hosting $^{26}\text{Al}$ at the time of their formation. CAIs, the first objects to form in the solar system are characterized by the canonical initial value of $5 \times 10^{-5}$. Objects that formed later, but before $^{26}\text{Al}$ become extinct, will be characterized by a lower value of initial $^{26}\text{Al}/^{27}\text{Al}$ ratio, a line with a lower slope. Terrestrial samples formed much after $^{26}\text{Al}$ was extinct will have a standard reference (terrestrial) $^{26}\text{Mg}/^{24}\text{Mg}$ value of 0.13932. (Catanzaro et al., 1966)

on different short-lived (e.g., $^{26}\text{Al}$, $^{53}\text{Mn}$, $^{182}\text{Hf}$) and long-lived ($^{235,238}\text{U}$) isotopes as chronometers (Halliday and Kleine, 2006, Thrane et al., 2006) argues against this proposition.

1.4 FORMATION OF EARLY SOLAR SYSTEM OBJECTS: THE PRESENT UNDERSTANDING

The tightly clustered initial $^{26}\text{Al}/^{27}\text{Al}$ ratio in CAIs within a narrow range around $5 \times 10^{-5}$ suggests a very small time interval (less than a few times $10^5$ years) for their
formation in the early solar system. Thus for any relative chronology of early solar system objects, the initial $^{26}\text{Al}/^{27}\text{Al}$ ratio of $5 \times 10^{-8}$ in CAIs is treated as the reference value. Even though chondrules are ubiquitous in chondrites, and an understanding of the time and duration of their formation is important for our understanding of early solar system processes, studies of Al-Mg isotope systematics in chondrules was hampered by the low abundance of phases with high Al/Mg ratio suitable to look for excess $^{26}\text{Mg}$ from $^{26}\text{Al}$ decay. Further, even within Al-rich glassy phases (mesostasis) in chondrules, the presence of Mg-rich microcrystalites makes the measurements difficult. The first observation of excess $^{26}\text{Mg}$ in a chondrule like object was first reported for a clast chondrule from Semarkona meteorite (Hutcheon and Hutchison, 1989); however, the first direct evidence for the presence of $^{26}\text{Al}$ in chondrules was provided by Russell et al. (1996). The data for Al-Mg isotope systematics in chondrules from UOC and carbonaceous chondrite currently available (Sheng et al., 1991; Hutcheon and Jones, 1995; Russell et al., 1996; Krot et al., 1999; Srinivasan et al., 2000; Kita et al., 2000, 2005a; Hutcheon et al., 2000; McKeegan et al., 2000b; Marhas et al., 2000, Huss et al., 2001; Mostefaoui et al., 2002; Kunihiro et al., 2004; Kurahashi et al., 2004) suggest that the highest initial $^{26}\text{Al}/^{27}\text{Al}$ ratio in chondrules is more than a factor of two lower than the canonical value for the CAIs. This would suggest that chondrule formation in the solar nebula took place $\sim$1 Ma following the formation of CAIs. As noted earlier, this is also supported by Pb-Pb dating of CV CAIs and CR chondrules by Amelin et al. (2002). However models are also proposed in which the formation of CAIs and Chondrules are considered to be contemporaneous (Shu et al., 1996).

Although the presently available data do suggest a time difference between formation of CAIs and chondrules, the exact magnitude of this difference and, more importantly, the duration for which chondrules formation sustained in the solar nebula remain contentious issues. Time scales of less than a Ma to greater than 4 Ma have been proposed as the duration of chondrule formation by various groups.
part of this spread could be due to secondary processes affecting the chondrules that can disturb the Al-Mg isotope records; however, this is both difficult to establish or to rule out conclusively. The long duration of chondrule formation exceeding 4 Ma, if true, have important implications for our understanding of the early evolution of solar system objects. I have therefore carried out a systematic study of chondrules from UOCs having petrologic grades of 3.0 to 3.3 to address the question of the onset and duration of chondrule formation in the solar nebula. Chondrules from UOCs of higher petrologic grades were avoided as Al-Mg isotope systematics in chondrules from Chainpur (LL3.4) revealed excess $^{26}$Mg in only one chondrule and lack of resolved excess in six other chondrules that suggest possible thermal perturbation in Mg isotope records in chondrules from UOCs of this grade (Huss et al., 2001). Chondrules from UOCs with petrologic grade 3.5 and above are devoid of $^{26}$Al record.

1.5 $^{26}$Al AS A HEAT SOURCE IN THE METEORITE PARENT BODIES

Even though there is a general consensus that chondrules from UOCs belonging to petrologic grade 3.0 to 3.3 should retain pristine Al-Mg isotopic record, our knowledge about post formation evolutionary history of the chondrules is not exact. It is not clear if the chondrules accumulate into large-sized (>km) planetesimals soon after formation or they had independent evolution either as an individual entity or as part of much smaller object (meter to kilometer) before being part of larger-sized meteorite parent bodies. Once the chondrules reside in larger size planetesimals they will experience heat generated within the parent body due to radioactive heating by $^{26}$Al and also $^{60}$Fe present in it. Because of its half life, $^{26}$Al will dominate the thermal evolution of meteorite parent bodies during their early evolution, while $^{60}$Fe will be a major source after a few Ma. The extent of heating by
these nuclides depends on the initial $^{26}\text{Al}/^{27}\text{Al}$ and $^{50}\text{Fe}/^{56}\text{Fe}$ at the time of formation of the meteorite parent bodies and their sizes. The phases (glass and rare plagioclase) analyzed for Al-Mg isotopes in UOC chondrules are typically $\sim 10 \mu m$. Mg isotope records in plagioclase can be disturbed over such a scale length at a temperature of $\sim 500 \degree C$ within a time period of about one Ma (LaTourrette and Wasserburg, 1998). Although no experimental data are available, the temperature for resetting Al-Mg isotope records in glassy phases may be lower than in plagioclase. I have therefore considered the possibility of specific pre-parent/parent body processes that may affect the observed $^{26}\text{Al}$ records in chondrules from UOCs of even lower petrologic grades that has been analyzed in this study.

1.6 The scientific objective and scope of this thesis

The initial studies of $^{26}\text{Al}$ records in chondrules from UOCs were concentrated on Al-rich chondrules that were followed by studies of the more common ferromagnesian chondrules (Hutcheon and Hutchison, 1989; Hutcheon et al., 1994; Russell et al., 1996; Kita et al., 2000; McKeegan et al., 2000b; Huss et al., 2001; Mostefaoui et al., 2002). Chondrules from UOCs belonging to LL group having petrologic grade 3.0 to 3.4 were analyzed in these studies. For the present work, I have selected nine UOCs belonging to both L and LL groups with petrologic grades ranging from 3.0 to 3.3. The particular samples analyzed are, Semarkona (LL3.0) and Bishunpur (LL3.1) that are falls, and finds from Algerian deserts Adrar-003 (L/LL3.1) and from Antarctica, namely LEW86134 (L3.0), QUE97008 (L3.05), LEW86018 (L3.1), Y-791324 (LL3.1), ALHA77176 (L3.2) and ALHA76004 (LL3.3) This work represents the first detail study of $^{26}\text{Al}$ record in chondrules from UOCs belonging to the L group.

Twenty nine chondrules selected out of more than two hundred chondrules from these meteorites were analyzed for Al-Mg isotope systematics to look for the presence of $^{26}\text{Al}$ in them at the time of their formation. The studies were carried out
using ion microprobe technique that allows isotopic analysis of microscopic phases ~5-10 μm in size, the typical size of the Al-rich phases in UOC chondrules.

The scientific objectives of the present work are:

(i) To understand the time of onset of chondrule formation in the early solar system using \(^{26}\text{Al}\) as a relative chronometer. The initial \(^{26}\text{Al}/^{27}\text{Al}\) ratio of \(5 \times 10^{-5}\) for refractory Ca-Al rich inclusions (CAIs), considered to be the first solids to form in the solar system, is treated as the reference value (MacPherson et al., 1995). This study along with data obtained in earlier work will allow a robust determination of the time of onset of chondrule formation in the solar nebula relative to the CAIs.

(ii) To estimate the duration of chondrule formation in the early solar system from the observed spread in initial \(^{26}\text{Al}/^{27}\text{Al}\) in chondrules from UOCs of low petrologic grades, obtained in this work as well as those reported earlier by others groups, assuming a uniform distribution of \(^{26}\text{Al}\) in the chondrule forming regions in the solar nebula.

(iii) To check whether the distributions in initial \(^{26}\text{Al}/^{27}\text{Al}\) in chondrules from various groups of UOCs (L and LL) and of different petrologic grades (3.0 to 3.3) are consistent with each other and to study plausible effect of thermal metamorphism in a pre-parent or parent body environment on the observed \(^{26}\text{Al}\) records in chondrules.

(iv) To place a limit on the active life time of the solar nebula defined as the time spanning the start of formation of CAIs to the cessation of chondrule formation.

The thesis consists of six chapters. Chapter 2 provides details of the various instruments such as ion microprobe, electron microprobe and scanning electron microscope and the experimental approach used in the present study. Descriptions of the analyzed chondrules along with their chemical composition are given in
chapter 3. Chapter 4 includes the results of Al-Mg isotope studies of chondrules from UOCs of various petrologic grades obtained using the ion microprobe. In Chapter 5, I present a discussion of the results along with their implications towards constraining the time of onset and the duration of chondrule formation in the solar nebula. The life time of the dynamically active solar nebula and the possible role of $^{26}$Al as a heat source and its possible impact on the observed $^{26}$Al records in certain chondrules are also discussed. A part of the work described in this thesis has been published recently (Rudraswami and Goswami, 2007). The last chapter provides a summary and conclusions of this work and outlines the scope for future work.