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Seasonal variations of dust record in the Muztagata ice cores

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Based on the oxygen isotope ratio and microparticle record in ice cores recovered at Mt. Muztagata, Eastern Pamirs, the seasonal variations of atmospheric dust have been reconstructed for the past four decades. High dust concentrations and coarser particle grains have the similar trend with oxygen isotope value. Our statistical results indicate that 50%—60% high dust concentration samples occur during the season with high oxygen isotope values (summer), while low dust storm frequency during spring and winter. Back-trajectory analysis shows that the air mass hitting Muztagata predominately came from West Asia (such as Iran-Afghanistan Plateau) and Central Asia, which are the main dust source area for Muztagata. Dust storms in those source areas most frequently occur during summer (from May to August), while frequent dust storm events in northern China mainly occur during spring (March to May). Regions in the path of Asian dust transport, such as in Japan, the North Pacific, and Greenland, also show high dust concentrations during spring (from March to May). Our results indicate that dust storms have different seasonality in different regions within Asia.

Muztagata, ice core, dust, seasonal variations

The Dust Belt in the Northern Hemisphere contains vast arid and semiarid regions from Sahara Desert eastward to the northern Chinese deserts and Loess Plateau[1]. There are two spatial scales to understand the Asian dust areas. On the global scale, Asian dust area differs from that in Africa and Australia. On the regional scale, Asian dust areas contain those dust emission regions, such as Taklimakan Desert, Qaidam Basin, Kazakhstan deserts, Gobi, etc. The seasonal distribution of dust emission of those regions is one of the key factors to its climatic forcing by altering the solar radiation budget and serving as fertilizer to some marine biological processes that may affect the global carbon cycle. Dust emission amount from the northern and northwestern Chinese deserts was estimated at 800Tg every year[2]. Atmospheric dust in ice cores can help for precise dating by their seasonal variations and provide an excellent indicator of past continental aridity and atmospheric circulation. Glaciers on the Tibetan Plateau, Pamirs, Tianshan Mts., and Altay Mts. contain amounts of glaciers and can provide reliable and high-resolution ice core records. Those glaciers are located close to Asian arid and semiarid regions and, due to their proximity to these dust sources, provide an excellent medium for the study of atmospheric dust deposition. Long-term Asian dust records have been studied through the study of microparticle samples from ice cores over the Tibetan Plateau, such as from Dunde[3], Guliya[4], Dasuopu[5] and Tianshan Mts.[6]. These studies display strong spatial difference in the properties, including the concentration, composition and seasonal variations, of dust over the Tibetan Plateau. For example, in Glacier No.1, Eastern Tianshan Mts., the coarse microparticle in weekly sam-

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pled surface snow samples has two high concentrations in the year, with one occurring from December to March, and the other occurring from June to September. And, the concentration of total microparticle occurs from April to August[6]. In the northern Tibetan Plateau, high dust concentrations occur during spring in Malan ice core, consisting to the frequent dust storm events in northern China, while in the southern plateau, it occurs in the non-monsoon season[7]. These researches indicate that in ice core records from western China mountains, high dust concentration season occurs asynchronously with regional variations.

Many researchers have focused on Eastern Asian dust[2,8−11], while little studies were given to the dust in Central Asia and West Asia. Dust in snowpack in the Pamirs have chemical compositions that are very similar to those in Arctic and Antarctica, suggesting that there may be a modern atmospheric background dust over the Pamirs[12]. Though the dust source areas are different for the loess sections from southern Tajikistan and Chinese Loess Plateau, their climatic records resemble similar trend over the past 1.77 Ma[13]. Those studies demonstrate that the Pamirs is an important region for study on atmospheric dust. This paper presents the dust data from ice cores recovered at Mt. Muztagata and clarifies the seasonal variations of dust over the Pamirs.

1 Sampling and method

From 2001 to 2003, we drilled several ice cores in accumulation area on a Muztagata glacier (38°17′N, 75°06′E) at different altitudes. In this paper, we discussed the 44.3 m ice core drilled at the elevation of 6350 m in 2002, and the upper 33.68 m of Core 3 (total length of 54.5 m) at an elevation of 7010 m. The environmental settings, samples preparation and laboratory analysis were well described in our previous papers[14,15] and will not be re-stated here. The extremely low air temperatures and ice core borehole temperatures for those ice cores limit the melting of surface snow and favor the preservation of environmental information (Figure 1).

Determining the implication of climatic proxy and dating are the two fundamental items of the explanation for ice core records. The upper level westerly prevails perennially above 5000 m height at Muztagata. Located in the central part of Asia continent, Muztagata is beyond the effects of Indian monsoon. Our team collected precipitation samples near the Mt. Muztagata base camp (4430 m) during the summer in 2002 and 2003 in order to measure δ^{18}O values and investigate their correlation with air temperatures. Precipitation at Muztagata comesmostly during June through September. The oxygen

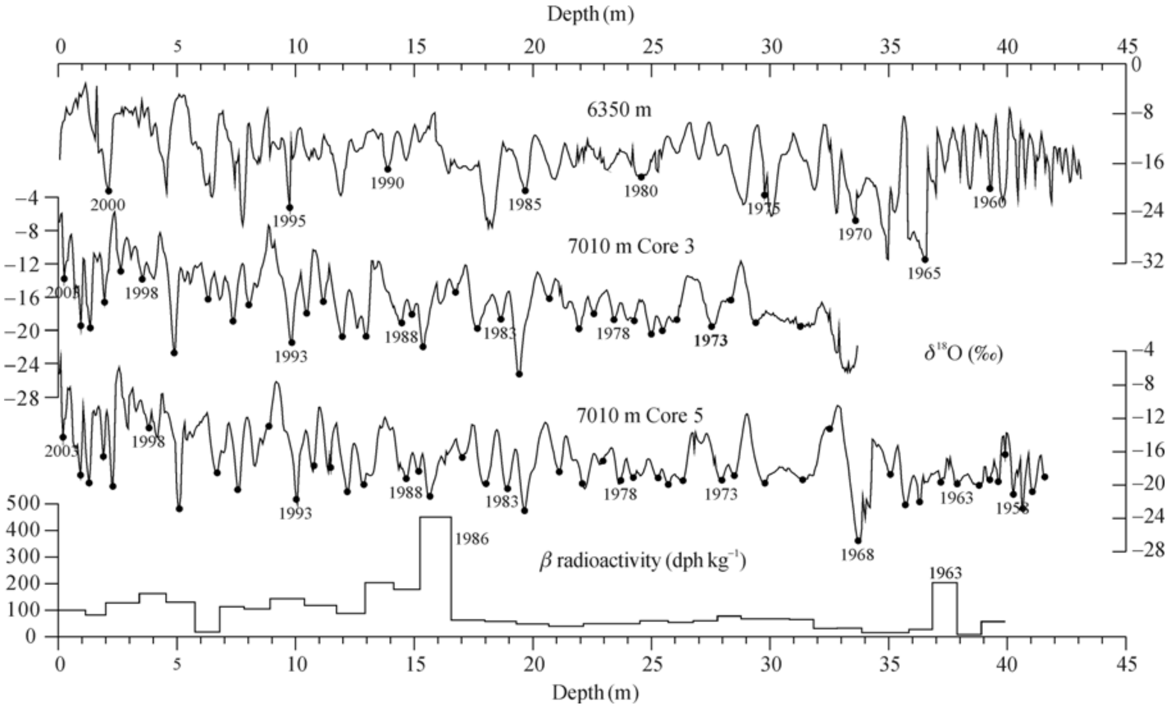

Figure 1 The oxygen isotope profiles, Beta activity, and dating results for three Muztagata ice cores. Black dots indicate annual dating boundaries. The data of 6350 m and 7010 m ice cores are from refs. [14] and [15], respectively.

isotope ratio in precipitation shows a strong temperature dependence, with high value during summer and low value during winter[15]. The δ^{18}O records provide the basis for identifying seasonal variations, which are apparent throughout the profile. However, enough winter precipitation (snowfall) also occurs and is well preserved at Mt. Muztagata to identify the low δ^{18}O values. We also collected scraped ice chips from 7010 m Core 5 for gross beta activity measurements. Two peaks of gross beta activity were found, at depths of 15.2—16.6 m and 36.9—37.9 m, corresponding to the 1987 Chernobyl nuclear accident and the 1963 nuclear bomb tests, respectively. Based on the gross beta activity peaks and seasonal variations of δ^{18}O, Core 5 was well dated, and Core 3 was dated by matching its δ^{18}O curve with Core 5's. Also the 6350 m ice core was dated using the seasonal variations of δ^{18}O profile and verified by curve matching with 7010 m Core 5. Due to the local environment, especially the elevation, oxygen isotope profile of the 6350 m ice core does not seem to resemble that of 7010 m. However, the annual averages of δ^{18}O value for the three ice cores resemble a close trend to the annual temperature at Tashkurgan during 1955—2000, verifying our dating results.

We have calculated the accumulation at 7010 m on Mt. Muztagata based on depth, density and dating results of Core 5. The averaged annual accumulation is about 605 mm (water equivalence) from the year 1955 to 2003, while the annual precipitation at Tashkurgan is only 69.3 mm. Precipitation rose with the increasing altitude in Mt. Muztagata and Mt. Kongur. During the 1980s, the total precipitation increased gradually with the elevation of the four meteorological stations, from 53.9 mm at 1288.7 m (Kashgar) to 375.2 mm at 3500 m (Yagaozi) in the middle mountain zone of this area[17]. Other studies estimated that the precipitation at 6000 m was 689 mm, and at 7000 m it might reach 1067 mm using the correlation between precipitation and elevation[18]. The former Soviet Union scientists found that the accumulation at 5400—6000 m on Communism Peak (now called Somoni Peak), Pamirs, could reach 940 mm. The accumulation at 6100, 6900 and 7200 m was estimated to reach 1080, 1340, and 700 mm, respectively[19]. These studies revealed that orographic factors have considerable impact on precipitation in this area and can cause multifold increase, reaching hundreds of millimeter in the high mountain areas of the Pamirs. This high accumulation in Muztagata ice cores clearly records the seasonal variations in the ice cores recovered here. This paper will discuss the seasonal characteristic of dust in Muztagata ice cores using the statistic method on the high dust concentration samples and seasons marked by the oxygen isotope ratio.

2 Results

The microparticle mass concentrations in the Muztagata Core 3 at 7010 m vary from 1133 to 63075 μg kg^{-1}, and in the 6350 m ice core they vary from 307 to 238905 μg kg^{-1}. Significant changes are well recorded in their profiles. Both the mass concentration and mean mass diameter resemble a similar trend to the oxygen isotope ratio, showing that high concentration and coarse grain mainly appear with high δ^{18} values. This suggests that higher dust load and stronger wind occur during summer over the Pamirs (Figure 2).

We categorized the high dust mass events by the corresponding δ^{18}O values to quantitatively show their seasonality. These correspond to increasing, maximum, and decreasing/minimum δ^{18}O value periods, roughly representing spring, summer, and winter seasons, respectively. We note that the three δ^{18}O value periods are relative, not absolute, since interannual variations of δ^{18}O are also distinct. The number of samples with mass concentrations >10000 μg kg^{-1} for the 7010 m ice core was chosen as an index to show the dust storm events recorded in the ice core for different seasons (Figure 3). Since microparticle concentration rises with the decreasing of altitude, samples with mass concentrations >15000 μg kg^{-1} were chosen as an index to show the dust storm events for the 6350 m ice core.

High concentration samples can occur sporadically and continuously (such as during 1973 and 1988). Statistical analysis shows that during spring, summer, and winter, the dust concentration peaks (>10000 μg kg^{-1}) from 7010 m core occur at approximately 19%, 46%, and 35% proportions, respectively, while dust concentration peaks (>15000 μg kg^{-1}) from 6350 m core show that dust storms occur at approximately 16%, 62%, and 22%, respectively (Table 1). Any standard to define the high dust concentration is subjective. When a higher concentration value is chosen as this standard, the statistical result will change somewhat. Furthermore, the records also indicate that using higher concentration stan-

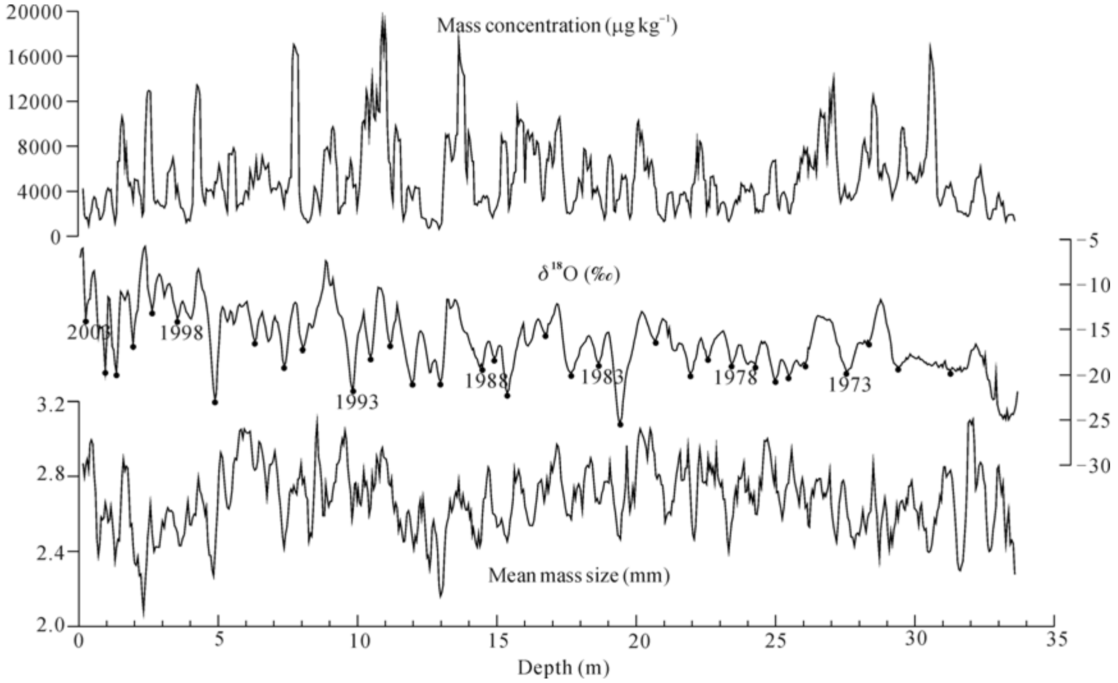

Figure 2 The dust concentrations and mean mass diameters (both after 5-points average) compared with δ^{18}O values in Muztagata Core 3, 7010 m. Black dots indicate annual dating boundaries.

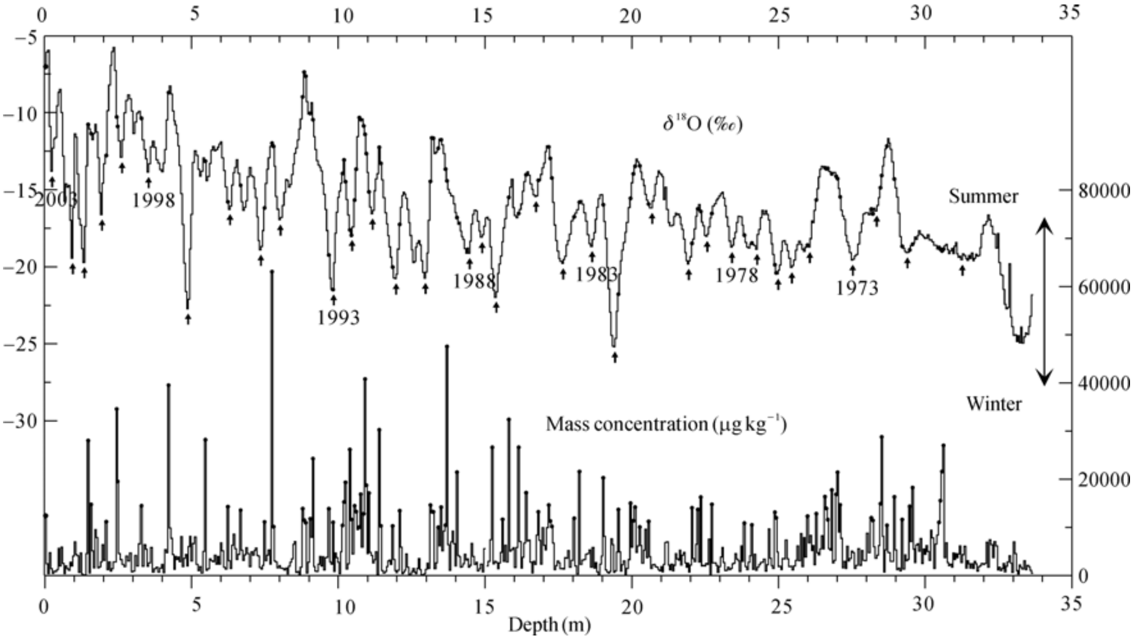

Figure 3 The δ^{18}O values and dust concentrations in Muztagata Core 3, 7010 m. Black dots indicate high dust concentration samples (>10000 μg kg^{-1}), while arrows show the annual dating boundaries.

Table 1 Statistical results for high dust concentration cases (frequency) in the Muztagata 7010 m and 6350 m ice cores

δ^{18}O period (season)	7010 m Core 3 (from 1970－2002 A.D.)			6350 m (from 1957－2000 A.D.)	
	>10000 μg kg^{-1} event (%)	>15000 μg kg^{-1} event (%)	>20000 μg kg^{-1} event (%)	>15000 μg kg^{-1} event (%)	>20000 μg kg^{-1} event (%)
Increasing (spring)	18 (19%)	11 (31%)	6 (30%)	15 (16%)	10 (17%)
Maximum (summer)	43 (46%)	18 (52%)	10 (50%)	56 (62%)	39 (66%)
Decreasing/minimum (winter)	33 (35%)	6 (17%)	4 (20%)	20 (22%)	10 (17 %)
Total	94 (100%)	35 (100%)	20 (100%)	91 (100%)	59 (100 %)

dards, high dust concentrations occur even less frequently during winter, while even more frequently during summer. However, the depositional processes and quantitative contributions between wet and dry deposition at Muztagata are still not entirely clear because of the lack of sufficient field observations and samplings. This may give some uncertainties to the explanation for dust records in ice cores. Since the precipitation mainly occurs in summer, the high summer dust concentration in ice core would reflect a much higher atmospheric dust load over Mt. Muztagata. Regardless of the detailed depositional processes, our results indicate that dust storms most frequently break out during summer.

3 Discussion

The source, transport path, composition, and spatiotemporal distribution of Asian dust provide basic and critical input to evaluate their climatic influences through the scattering and absorption of radiation and fertilizing the oceans. In different dust source areas, those properties are basically controlled by their natural environment and climate patterns. Different parts of Asia arid and semiarid regions have different dust emission amounts and contributions. The composition of dust samples from fresh snow near the NorthGRIP drilling site in Greenland indicated that the Taklimakan Desert is the primary source during the dusty spring, while the Tengger and Mu Us deserts play a role during most of years and during the low-dust season (summer through winter)[20]. This suggests that the regional characteristics for Asia arid areas are important for the comprehensive understanding of Asian dust's impact on and response to the climate.

Numerous previous studies on Eastern Asian dust demonstrated that most frequent dust storm events and high dust concentrations in Eastern Asia and at different sites on the dust transport path occurred during spring (from March to May and peaked in April). Those studies include the strong dust storm frequency in northern China[8], the seasonal variation of dust in snow collected at Mt. Tateyama, Central Japan[9], the atmospheric dust concentration in North Pacific[10], and the crustal cations in snowpack near NorthGRIP in Greenland[11]. The Malan ice core in the northern Tibetan Plateau also shows that the dirty layers mainly occur in the spring, indicating that the dust load is higher during spring than other seasons[7].

Though close to the west part of the Taklimakan Desert, the Muztagata receives little dust from there. The prevailing near-surface winds in west part of this desert are northwesterly, while the prevailing high level winds are perennial westerlies. Under those winds, dust entrained from the Taklimakan Desert is transported and accumulated on the northern windward slopes of the Kunlun Mountains[21]. The average 500 hPa circulation in July and January over the Pamirs is high level westerlies. The back-trajectory analysis (for 72 or 120 hours) at an interval of week between June 2004 and April 2006 shows that the predominate air mass hitting Muztagata mainly came from West Asia (such as Iran-Afghanistan Plateau) and Central Asia, some from the north of Pakistan and India, only once from the Taklimakan Desert. Based on this, it is reasonable to conclude that the major dust source areas are Central Asia and Iran-Afghanistan Plateau or further west, while the Taklimakan Desert only contributed little amounts of dust. However, to detect the exact potential source areas is complex and needs the geochemical data of those dusts.

Central Asia and Iran-Afghanistan Plateau ranges from steppe to desert, with large areas of the region receiving little precipitation. The Mediterranean climate prevails in those regions. Precipitation generally occurs between November and May, while very little or no precipitation occurs between June and September, during which air temperatures are high. Persistent dust activities in the region between the Caspian and Aral Seas generally start in May and last through August with the peak activity in June and July[1]. The maximum number of days with dust storms in Turkmenistan occurs between May and August, making up 62% of the annual total[22]. The aerosol optical depth over Issyk-Kul Lake (Kyrgyzstan) during the past four years shows an increase from May through September, which usually peaks during July[23]. Dust storms are prevalent through the high Iran-Afghanistan desert plains in summer, often associated with what has been referred to as the 'wind of 120 days', the highly persistent winds during the warm season[24]. The warm and dry climate makes soil conditions more favorable for the dust storm formation that can entrain and transport considerable dust to the leeward areas. The present meteorological observations indicate that in Central Asia and Iron-Afghanistan, dust storm events most frequently occur during summer, showing consistency with dust records in Muztagata ice cores. Moisture trajectory modeling for the precipitation of 2003 summer shows that the moisture origins for the Muztagata region were controlled by the westerlies[25]. This suggests that dust materials carried with the moisture also were transported by westerlies. In the Muztagata region, the precipitation comes mostly during June through September, which favors wet deposition of dust by enhanced scavenging processes.

Different geographical and climatological settings are the fundamental factors that influence the dust storm season. The dust concentrations recovered from Muztagata ice cores are well defined and clearly show that most frequent dust storms for Central Asia and Iran-Afghanistan occur during summer, especially during July through August. This frequent dust storm season distinctly lags behind that in Eastern Asia (March—May) and the dust peak concentrations in the North Pacific and Greenland (spring). Saharan dust, which comes from far west of Central Asia and West Asia, can occasionally be transported long distances eastward by mid-latitude westerlies to western North America[26]. It is reasonable to draw a conclusion that Central Asia and Iran-Afghanistan have dust contribution to the North Pacific and further. However, since the amount of dust emission is much low in Central Asia and Iran-Afghanistan regions than that in northern China (the latter accounts for about half of the world total[2]) and the intensive precipitation in Eastern Asia intensifies dust scavenging during summer, only a minor amount of dust from the West and Central Asia arid regions can be transported to the North Pacific.

4 Conclusion

The Muztagata ice cores recorded visible seasonal variations of oxygen isotopes and dust concentrations over the Eastern Pamirs. Air mass back-trajectory modeling shows that the West and Central Asia regions are the major potential source areas for Muztagata dust. Statistical results show that in the Muztagata ice cores, the high dust concentration peaks and coarser particle grains mainly appear with high δ^{18}O values, indicating that the dust storm events mainly occur during summer (accounting for about 50%—60% of the annual total) while low dust storm frequency appears during spring and winter. This timing of frequent dust storm in West and Central Asia shows a distinct lag compared to dust storm season in northern China, North Pacific, and Greenland (where the dust storm mainly occurs from March to May). Our results demonstrate the asynchrony for the timing of frequent dust storm events in different parts of Asia arid and semiarid areas. Such understanding has potential implications for our comprehension of the correlations and mechanisms between Asian continental dust and climate.

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TREND

Announcing a Special Issue on *Bulk Metallic Glasses* in Science in China Series G: Physics, Mechanics and Astronomy

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An amorphous metallic alloy, also called metallic glass, is a kind of metallic matter without long-range atomic order. A glassy state exists in almost all matter, but it is hardly reached in metallic alloys. That is why the preparation of glassy materials has a history of several thousand years, while that of metallic glass began only a few decades ago. With a disordered atomic structure, metallic glass has the combined characteristics of solid and liquid, and of metal and glass, which gives it quite unique mechanical, physical, and chemical properties. Therefore, metallic glass, in particular bulk metallic glass material has drawn much attention since its discovery, and has found broad applications in various fields over the past decades. The study of metallic glass became also a hot topic of condensed matter physics. Now glass physics, or alternatively, the physics of the amorphous state, has become one of the frontier subjects both in materials science and condensed matter physics.

In recent years, under the support of the National Natural Science Foundation of China, the Ministry of Science and Technology of China, and the Chinese Academy of Sciences, many research groups in China have been engaged in developing new metallic glass materials and in studying the relevant issues; they have made great achievements in the preparation of the material and the analysis of its structure and physical properties. Today, Chinese scientists are ready to prepare a variety of large-sized bulk metallic glass systems, and their achievements in the analysis of the structure, formation, and mechanical and physical properties of bulk metallic glass have attracted broad international interest and attention.

This special issue is a representative review of the most important research results of the key research groups in China, and it tries to cover almost all aspects of metallic glass, including amorphous structure, preparation techniques, exploration of new materials, mechanical and physical properties, and the like. We hope that this special issue can display the latest progress in metallic glass research in China, and that it will also promote communication and cooperation in this field.

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