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Ungrouped Iron Meteorites in Antarctica: Origin of Anomalously High Abundance

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Eighty-five percent of the iron meteorites collected outside Antarctica are assigned to 13 compositionally and structurally defined groups; the remaining 15 percent are ungrouped. Of the 31 iron meteorites recovered from Antarctica, 39 percent are ungrouped. This major difference in the two sets is almost certainly not a stochastic variation, a latitudinal effect, or an effect associated with differences in terrestrial ages. It seems to be related to the median mass of Antarctic irons, which is about 1/100 that of non-Antarctic irons. During impacts on asteroids, smaller fragments tend to be ejected into space at higher velocities than larger fragments, and, on average, small meteoroids have undergone more changes in orbital velocity than large ones. As a result, the set of asteroids that contributes small meteoroids to Earth-crossing orbits is larger than the set that contributes large meteoroids. Most small iron meteorites may escape from the asteroid belt as a result of impact-induced changes in velocity that reduce their perihelia to values less than the aphelion of Mars.

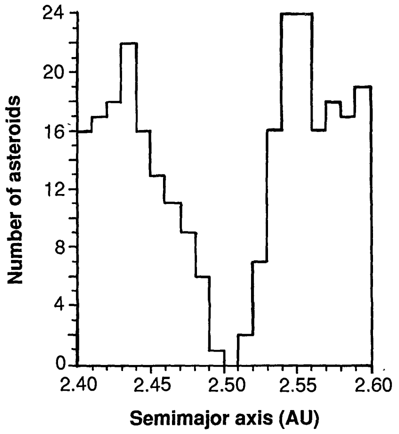

Fig. 1. The quantity of numbered asteroids increases rapidly with increasing deviation of the semimajor axis from that (2.501 AU) corresponding to a 1:3 period resonance with Jupiter. Semimajor axes are from the compilation by Bender (*18*).

IRON METEORITES ARE CLASSIFIED ON the basis of their structures and detailed compositions (*1*). In all, 13 groups of five or more meteorites have been identified, but 15% of the iron meteorites cannot be so classified and are called "ungrouped" (the choice of five as the minimum number required to form a group is arbitrary). Meteorites in 10 of the 13 groups seem to have formed by the fractional crystallization of large metallic magmas on separate parent bodies. The origin of the meteorites in the remaining 3 groups is not settled; they may have formed as individual pools of shock melt (*2*). Strong interelement correlations are observed in each group; slopes on element-Ni trends are generally higher in the magmatic than in the nonmagmatic groups. For some elements (Co, Cu, and especially Ga and Ge), the total compositional variation in most groups is much smaller than that between groups; thus, these elements are useful taxonomic parameters.

The ungrouped irons have compositions that place them distinctly outside the group fields on most element-Ni diagrams. Generally the structures (for example, kamacite bandwidths and the nature and content of nonmetallic phases) are also inconsistent with membership in the groups that have the most similar contents of the taxonomic elements. It is convenient to designate sets of one to four compositionally related irons as "grouplets." Each of these grouplets also appears to have formed in a separate parent body. Roughly 40 asteroidal parent bodies are required to account for the 100 ungrouped irons; thus, 50 to 55 asteroids are needed to account for the 605 characterized iron meteorites. Stony meteorites show less diversity; the characterized set requires about half as many parent bodies as the irons.

Clarke (*3*) recognized that the fraction of ungrouped irons in the set from Antarctica was much larger than that of irons from the remainder of the world. Wasson *et al.* (*1*) confirmed this observation and expanded the characterized set (8 ungrouped in a total of 24 Antarctic irons) and discussed mechanisms that could account for the enhanced abundances. I report data for seven additional Antarctic irons (including four ungrouped); thus, the ungrouped fraction is now 12/31 or 0.39. Because each of the 12 Antarctic ungrouped irons has a different composition, the large fraction of ungrouped irons cannot have resulted from atmospheric breakup, a process that could be responsible for the anomalously high fraction of H chondrites in Victoria Land, Antarctica (*4*).

Two of the seven new Antarctic irons (Table 1) are typical group members: IIIAB GRO85201 and IIICD LEW86540. The composition of another one, EET87506, places it within IAB fields on most element-Ni diagrams, but its Ir content is about three times as high as that expected, and its structure is anomalous. The remaining four irons are ungrouped; their compositions differ in numerous ways from those observed in groups having the most similar Ga and Ni contents. Compared to mesosiderite metal nodules having a similar Ni content, Ir in ALH84233 is low by a factor of 100, and Co, As, and Au are about 1.2 times as high. Meteorite EET87516 has a structure and Ga content similar to those of group IVA irons, but its Ir content is too high by a factor of 10, its Co content is high by a factor of 1.2, and its Ga content is low by a factor of 1.2 for an IVA iron with a Ni content of 92 mg/g.

One of the most interesting of the new irons is LEW85369, which contains Si dissolved in the Fe-Ni metal; in this and most other compositional respects, LEW85369 resembles the ungrouped Horse Creek iron meteorite and the ungrouped metal nodules from the Mount Egerton stony-iron meteorite. The LEW86211 iron contains ~62% FeS by volume (*5*), after Soroti the second highest percentage in an iron meteorite. It is compositionally most similar to the low-Ni extreme of group IIE but is deviant on most element-Ni diagrams; for example, Ir and W are 34 and 1.5 times as high, respectively, as the highest IIE values.

In all, 88 of the 574 non-Antarctic irons are ungrouped (*1*), a fraction of 0.153. If the probability that any randomly chosen iron is ungrouped is 0.153, the probability of finding ≥12 ungrouped irons in a set of 31 is 0.0013. It is thus very unlikely that the Antarctic irons are sampling the same population as the non-Antarctic irons.

It is not possible to account for the high

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Table 1. Classification, kamacite bandwidth (BW), structural category (Struc), and elemental concentrations in seven iron meteorites from Antarctica; Ungr, ungrouped; otherwise, group class is given; Anom, anomolous; Off, finest octahedrite; Om, medium octahedrite.

Meteorite	Class	BW (mm)	Struc	Cr (μg/g)	Co (mg/g)	Ni (mg/g)	Cu (μg/g)	Ga (μg/g)	As (μg/g)	Sb (ng/g)	W (ng/g)	Re (ng/g)	Ir (μg/g)	Pt (μg/g)	Au (μg/g)
ALH84233	Ungr	>5	Anom	12	5.39	64.6	168	14.0	14.4	260	985	<30	<0.003	<0.7	1.07
EET87506	IAB-an		Anom	34	5.37	205.	921	22.1	28.6	2760	350	279	3.05	5.7	1.96
EET87516	Ungr	0.03	Off	340	4.84	93.0	176	1.76	6.28	<50	840	700	6.40	9.6	0.92
GRO85201	IIIAB	1.1	Om	18	5.15	84.7	146	20.0	7.41	<50	570	<30	0.360	6.2	1.01
LEW85369	Ungr		Anom	186	3.33	74.2	318	46.8	13.4	420	690	350	3.49	6.3	1.49
LEW86211	Ungr		Anom	580	3.97	69.7	361	28.4	11.6	320	2030	2540	23.4	22.9	1.05
LEW86540	IIICD	0.035	Off	12	5.93	187.1	459	4.31	29.6	730	<80	<30	0.044	<1.3	1.81

ungrouped fraction of Antarctic irons by postulating that ungrouped irons exclusively populate a unique set of interplanetary orbits. As shown by the calculations of Halliday and Griffin (*6*), meteoroids originating in orbits having any reasonable set of orbital parameters will be distributed over a large latitudinal range. This reflects in part the effect of gravitational focusing, in part the precession of the poles of the orbits and of Earth's spin axis, and particularly the 23.5° obliquity of Earth's axis. Even fragments having nearly identical orbital elements yield fluxes 45° off the "target latitude" that are 74 to 84% of the maximum flux [figure 1 in (*6*)].

Antarctic iron meteorites have been recovered between 70° and 80°S, and the 145 irons recovered from 20° to 55°S in Africa, Australia, and South America (*7*) form a reasonable comparison set separated by a mean latitudinal difference of about 45°. Only 13 (11.5%) of these are ungrouped, despite the expectation that they share similar orbital parameters with the Antarctic irons. Because there is no known mechanism that would tend to place ungrouped irons into unusual orbits and because even relatively extreme orbits cannot account for the much higher ungrouped fraction in Antarctica, it is highly unlikely that latitudinal effects are responsible for the observed difference.

Antarctic iron meteorites are not resolvably different from non-Antarctic irons in their terrestrial age ranges; thus, this cannot be the explanation for their differences in distribution among classes. Data for 17 independent Antarctic irons (*8*) yield a median terrestrial age of 110 ka (thousand years ago); because a large fraction has been studied, this median age appears to be free of selection bias. Non-Antarctic irons (*9*) have a median age of 200 ka, older than that for the Antarctic irons, but the non-Antarctic set appears to be biased toward older ages because many are from dry climatic zones, and a properly weighted median terrestrial age would probably be similar to that for the Antarctic set. Even if the median age of non-Antarctic meteorites were later discovered to be several times smaller than that of Antarctic irons, this would not imply differences in the populations, because the Antarctic terrestrial age is two orders of magnitude smaller than the orbital lifetime of interplanetary objects in Earth-crossing orbits, about 10 million years (*10*).

Mass seems to be the key property that differs between the two sets of iron meteorites. The median mass of Antarctic irons (300 to 400 g) is only about 1/100 that of non-Antarctic irons, which average ~30 kg (*11*). This difference is not surprising, because small (≤200 g) meteorites easily escape detection in woods and fields (although during the past three decades a number of small stony meteorites have called attention to themselves by penetrating roofs), but are readily spotted on the surface of ice. Loss of Antarctic irons by settling through the ice is negligible. Even irons having masses of 1000 kg will only sink ~100 m through the ice in 10^6 years (*12*).

The median mass of the Antarctic ungrouped irons is not significantly different from that of the grouped irons, but the five largest irons are grouped. The largest of the 12 ungrouped irons is Lazarev at 10.0 kg. The number of irons with masses of <200 g is similar: 5 of 12 ungrouped versus 10 of 19 grouped irons. Thus, the mass distributions of grouped and ungrouped Antarctic irons are at most marginally different, consistent with similar mass distributions (and similar strengths and fragmentation characteristics) in space.

The statistical distribution among non-Antarctic irons supports the conclusion that the ungrouped fraction is higher for small irons. On the basis of catalog information (*7, 11*), Wasson (*13*) compiled a list of irons having recovered masses of <1000 g. The original masses of several of these irons are no longer known, and it is probable that some large meteoroids are erroneously included. Recent data eliminate IAB Alexander County from the list; the revised ungrouped fraction is 7/29, or 0.24. The ungrouped fraction for irons having masses ≥1000 g is 0.148.

Consideration of the processes by which meteoroids are transferred from the orbits of their parent asteroids (dynamic lifetimes 10^9 years) into Earth-crossing orbits suggests reasons why the set of small meteoroids should be more diverse than that of large meteoroids. The escape velocity for a chondritic asteroid with a 100-km radius is about 140 m/s (*14*). Impact cratering events can eject large (~25 m) blocks with velocities of at least 600 m/s without comminuting the ejecta (*15*); the recovery of lunar meteorites shows that fragments having dimensions of several centimeters can survive ejection even at velocities above the lunar escape velocity of 2400 m/s.

Two arguments indicate that, on average, the ejection velocity of small fragments is greater than that of large fragments. A minor velocity enhancement results because, in each cratering event, there is a small increase in mean ejection velocity with increasing ejecta size. A more important effect is that, the higher the velocity of impact, the higher the mean ejection velocity and the lower the mean size of the ejecta (*16*). Thus, from each asteroid smaller fragments are ejected into a broader range of orbits than larger fragments.

Two main source regions for meteorites are probably the asteroids near period resonances with Jupiter and those with perihelia near the orbit of Mars (*17*). Asteroids or meteoroids having periods close to the 1:3 resonance with Jupiter's period [semimajor axes between 2.48 and 2.52 astronomical units (AU)] can have chaotic orbits that rapidly become Earth-crossing. This source can account for many of the meteoroids captured by Earth.

Figure 1 shows the asteroid orbital population near the 1:3 resonance (*18*). In this region, a change in the velocity of 75 m/s parallel to the orbital velocity vector corresponds to a change in the orbital semimajor axis of 0.02 AU. Ejecta that receive impulses of this magnitude can enter the 1:3 resonance escape channel from asteroids having semimajor axes between 2.46 and 2.48 or between 2.52 and 2.54 AU. For ejecta having velocities of 75, 150, and 225 m s^{-1}, the cumulative number of potential source asteroids is 43, 120, and 194, respectively (Fig. 1); it is clear that the higher the ejection velocity, the greater the number of asteroids that can supply meteoroids to the escape channel. Because there are no known processes that would lead to extensive intermixing of diverse asteroids near the center of the Asteroid Belt, it seems likely that there are relatively few classes of iron meteorites near the 1:3 resonance. In addition, most asteroids may have silicates on their surfaces; thus, this comparison of the number of asteroids that can be sampled probably overestimates the diversity of iron meteorites that this mechanism could yield.

The second escape channel involves perturbations of meteoroids into Earth-crossing orbits resulting from close encounters with Mars (*17, 19*). Williams and Hierath (*20*) noted that 3% of the small PLS (Palomar-Leiden Survey) asteroids have perihelia that during some epochs are inside the aphelion of Mars; a much larger fraction have perihelia within a few tenths of an astronomical unit of the martian orbit. There are two reasons why a greater diversity of iron meteoroids might be found in asteroids having small semimajor axes and relatively eccentric orbits. (i) The heat sources (such as solar wind–induced currents, ^{26}Al decay, or interasteroid collisions) all increase in effectiveness with decreasing distance to the sun; thus the proportion of differentiated asteroids formed at ≤2 AU should be significantly greater than that formed at greater heliocentric distances (*21*). (ii) The weak gravitational field of Mars is well suited to trap asteroids from elsewhere in the inner solar system into long lifetime (>10^9 years) storage orbits, an appreciable number of which will have survived until the present (*10*).

The data of Williams and Hierath [figure 5b in (*20*)] showed that 39 PLS asteroids cross Mars aphelion (~1.7 AU). An additional 35 have perihelia within 0.04 AU of Mars, 47 have perihelia 0.04 to 0.08 AU, and 80 have perihelia 0.08 to 0.12 AU from the orbit of Mars. Impact cratering of these asteroids is most likely near aphelion in the densely populated part of the asteroid belt. To reduce the perihelion by 0.04 AU, the aphelion velocity must be reduced by about 110 m/s. The cumulative number of potential parent asteroids increases rapidly with increasing ejection velocity.

The change in orbital velocity need not occur in a single impact event. After their initial liberation, large (>10 m) meteoroids will collide with comparably sized objects; such events will often involve additional fragmentation. Each of these jostlings will result in changes in the orbital parameters and a random-walk change in these parameters away from those of the parent body. Clearly, the more jostling events a meteoroid has undergone, the greater the mean change in its orbital parameters. On the average, the smaller the meteoroid, the more jostlings it will have experienced.

In summary, both the primary ejection from the parent body and the subsequent collisions with small space debris will cause the orbits of smaller meteoroids to differ more from those of the parent asteroids than do those of larger meteoroids. As a result, the number of parent asteroids providing small debris to the channels that allow escape from the asteroid belt will be greater than the number parental to the large meteoroids reaching these channels. The Antarctic meteorite collection is particularly valuable because it has a much higher efficiency for the collection of these unusual meteoroids having small masses (*22*).

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Slow Mortality Rate Accelerations During Aging in Some Animals Approximate That of Humans

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A general measure of the rate of senescence is the acceleration of mortality rate, represented here by the time required for the mortality rate to double (MRD). Rhesus monkeys have an MRD close to that of humans, about 8 years; their shorter life-span results mainly from higher mortality at all ages. In contrast, some groups with short life-spans (rodents and galliform birds) have shorter MRDs and faster senescence. On the basis of the Gompertz mortality rate model, one may estimate the MRD from the maximum life-span (t_{max}) and the overall population mortality rate. Such calculations show that certain birds have MRDs that are as long as that of humans. These results show that high overall mortality rates or small body sizes do not preclude slow rates of senescence.

ACCELERATIONS OF THE ADULT mortality rate during aging (*1–5*) parallel the increasing incidence of spontaneous degenerative diseases in humans and certain rodents (*6,7*). It is inferred from comparisons of maximum life-spans (t_{max}) that the rate of senescence slowed during evolution in human ancestors, as well as in other mammals (*8–10*). Because t_{max} depends on the acceleration of mortality rate