larly poorly. Because the smaller D_2 is, the larger is the departure from a uniform space-filling distribution, these results mean that clusters of galaxies have stronger correlations than optical galaxies, which, in turn, have stronger correlations than IRAS galaxies. It is natural to interpret these trends in terms of multiscaling of objects identified in terms of different richness thresholds. A self-consistent picture emerges in which clusters correspond to higher matter densities than typical optical galaxies, which are themselves located (on average) in denser environments than IRAS galaxies. Even the apparently anomalous behavior of EDCC is consistent with this trend: clusters from this sample are, on average, richer than in the other cluster samples, so its behavior confirms the multiscaling of clusters of different density seen in the simulations we have already described.

An important point to emerge from this analysis is that the most natural and effective way to characterize scaling properties of the clustering of objects of different intrinsic richness is through the correlation integral $C(r)$ rather than the two-point correlation function $\xi(r)$. Although differences in the two descriptions are small if $\xi(r) \gg 1$, in the regime where $\xi \approx 1$, no distribution can simultaneously display scaling of both $\xi(r)$ and $C(r)$. The correlation integral description allows a wide range of empirical clustering data to be unified into a single coherent framework within which multiscaling is a natural consequence. For example, the fact that D_2 for IRAS galaxies is larger than that for optical samples indicates that IRAS galaxies are less correlated than optical galaxies, or in other words, that optical galaxies correspond to higher peaks of the density distribution.

Using Eq. 4, we can obtain clean estimates of r_0 for these data sets. For the ACO sample, we get $r_0 \approx 23h^{-1}$ Mpc, and for the Abell sample, $r_0 \approx 26h^{-1}$ Mpc in the range $10h^{-1}$ to $50h^{-1}$ Mpc, whereas for the APM cluster catalog, we get $r_0 \approx 16.7h^{-1}$ Mpc in the range $1h^{-1}$ to $40h^{-1}$ Mpc, in agreement with the value reported by Dalton *et al.* fitting $\xi(r)$ directly to a power law (*9*).

What is missing at the moment from this approach is a detailed understanding of the way initial conditions and dynamics interact to produce the observed scaling properties. Nevertheless, the ability to incorporate the dependence of clustering strength on richness into a unified multifractal scaling paradigm through the multiscaling hypothesis is a considerable benefit of this approach. Moreover, the robustness of $C(r)$ scaling compared to that of $\xi(r)$ strongly motivates the use of $C(r)$ as a diagnostic of clustering pattern and dynamics. Only by the use of appropriate statistical tools such as this will the new generation of galaxy redshift surveys lead to a theoretical understanding of the origin of large-scale structure in the universe.

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Biological Controls on Coral Sr/Ca and $\delta^{18}O$ Reconstructions of Sea Surface Temperatures

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Coral strontium/calcium ratios have been used to infer that the tropical sea surface temperature (SST) cooled by as much as 6°C during the last glacial maximum. In contrast, little or no change has been inferred from other marine-based proxy records. Experimental studies of the effect of growth rate and the magnitude of intraspecific differences indicate that biological controls on coral skeletal strontium/calcium uptake have been underestimated. These results call into question the reliability of strontium/calcium–based SST reconstructions.

Paleoclimate reconstructions of tropical SSTs during the last glacial maximum (LGM) have produced contradictory results: Continental temperature proxy records suggest that the tropics were 4° to 6°C colder during the LGM (*1*), as opposed to estimates from planktonic microfossil assemblages, which suggest little or no change (*2*). The resolution of this discrepancy is key to establishing the sensitivity of the tropics to global climate change (*3*). The Sr/Ca content of coral skeletons has recently been used as a proxy for SST (*4*, *5*). The basic principle is that the correlative relation between coral Sr/Ca and SST can be applied to fossil coral specimens to reconstruct SSTs in paleoenvironments. The Sr/Ca measurement precision of <0.1%, equivalent to ~0.1°C, is 10 times that of other paleothermometers (*4*). The Sr/Ca results suggest that the tropical western Pacific and western Atlantic were 4° to 6°C cooler during the LGM than today (*4*, *5*); this estimate is in agreement with terrestrial temperature proxy records but contradicts other marine-based records (*1*–*3*).

Two key assumptions are made in apply-

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ing the Sr/Ca thermometer. These are that (i) temperature is the primary control on coral skeletal Sr/Ca uptake, and biological controls are negligible, and (ii) the Sr/Ca content of seawater is constant on glacial-interglacial time scales. However, the Sr/Ca content of surface seawater on latitudinal transects in the Atlantic and Pacific Oceans has recently been shown to vary by ~2% between 10°S and 30°N, which represents an uncertainty of 2° to 3°C in the Sr/Ca thermometer (*6*), and other studies have shown that coral skeletal Sr/Ca and $\delta^{18}O$ values are subject to growth and calcification rate effects (*7*, *8*).

To address the uncertainties associated with the effect of growth rate on coral Sr/Ca and $\delta^{18}O$, we examined a *Pavona clavus* head collected at a depth of 14 m at Punta Pitt in the Galápagos Islands (*6*, *9*). Samples for Sr/Ca and $\delta^{18}O$ analyses were taken from this specimen along synchronous growth transects with different extension rates (*10–14*). This strategy allows an evaluation of growth rate effects that is independent of the in situ temperature and variations in seawater Sr/Ca. Although seasonal variations in skeletal Sr/Ca covaried among the different transects, the slower growing transects had higher Sr/Ca values. As a result, a single Sr/Ca-SST relation with a predictive value equivalent to the Sr/Ca measurement precision cannot be established (Fig. 1A). For extension rates of 6 and 14 mm/year, the apparent temperature offset associated with the different ratios would be 2° to 4°C. Similarly, skeletal $\delta^{18}O$ values obtained along the slower growing transect were more enriched in ^{18}O (Fig. 1B). The apparent temperature difference from the $\Delta\delta^{18}O$ values between the 6 mm/year and 12 mm/year transects is equivalent to 1° to 3°C. This result contradicts the current notion that oxygen isotope kinetic fractionation is constant above extension rates of ~2 mm/year (*15*), and therefore also argues against the suggestion that because skeletal Sr/Ca but not $\delta^{18}O$ is dependent on the extension rate, the Sr/Ca and $\delta^{18}O$ values provide independent estimates of SST (*5*). Our results are supported by some earlier studies that also concluded that growth or calcification rate is an important control on the isotopic composition of coral skeletons (*8*). Given conditions that result in slow extension rates, both thermometers would thus tend to be biased toward indicating colder temperatures than were actually experienced.

To test the assumption that the growth rate effect on coralline Sr/Ca can be circumvented by sampling corals with similar extension rates (*4*, *5*, *16*), we examined three *Porites lobata* specimens with extension rates of ~12 mm/year from Oahu, Hawaii, two (~20 m apart) at Koko Head and one at Kahe Point. Long-term temperature records at these sites show a high degree of covariation (r = 0.97), with Kahe Point ~0.3°C warmer than Koko Head (*6*); this was taken into account in the following comparison. Seawater analyses showed no measurable difference in Sr/Ca content between the two sites (*6*, *9*). Sr/Ca analyses along synchronous growth transects produced three significantly different trends in Sr/Ca values and thus Sr/Ca-SST calibrations (Fig. 2, A and B). The difference within the same reef (Koko-1 and Koko-2) was as much as 2° to 3°C. Also, although the seasonal ΔSST was 3°C at both sites, the seasonal ΔSr/Ca values differed significantly, with values at Koko Head 13 to 40% smaller than those at Kahe Point. It may be argued that these intraspecific differences in Sr/Ca uptake are to some extent the result of small-scale SST variations within the reef. Although this is unlikely to be the case at sites such as Koko Head, which are characterized by intense mixing, this uncertainty associated with coral-based reconstructions must be acknowledged. If the intraspecific differences are biological in origin, the controls on Sr/Ca uptake are likely very complex and difficult to predict. Both sources of uncertainty would limit the interpretation of Sr/Ca values in fossil coral specimens.

We have demonstrated that variations in the Sr/Ca content of seawater and biological effects can induce uncertainties of 2° to 3°C in temperature estimates, equivalent to at least half of the glacial-interglacial tropical SST change predicted by the Sr/Ca thermometer. Some earlier studies suggested that the Sr/Ca relation to temperature is an indirect response to the more direct influence of temperature on photosynthetic and metabolic processes (*7*, *8*). The meta-

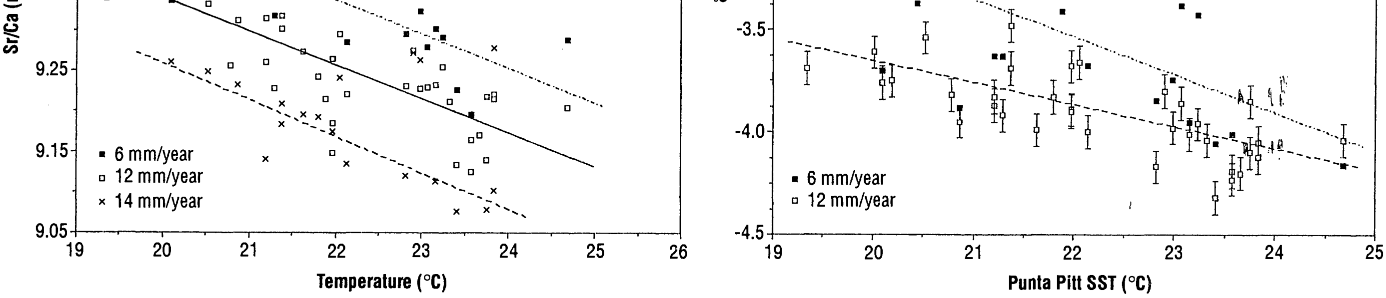

Fig. 1. (**A**) Linear relation between skeletal Sr/Ca and temperature in *Pavona clavus* along three different growth transects with annual extension rates of 6, 12, and 14 mm/year, respectively. Sampling and analytical techniques are described in (*7*) and (*10*). The [Sr/Ca]-temperature (T) regression lines along the transects are $[\mathrm{Sr/Ca}]_{6\ \mathrm{mm/year}} = 10.25 - 0.0417T$ (r = 0.89), $[\mathrm{Sr/Ca}]_{12\ \mathrm{mm/year}} = 10.11 - 0.0388T$ (r = 0.88), and $[\mathrm{Sr/Ca}]_{14\ \mathrm{mm/year}} = 9.92 - 0.0331T$ (r = 0.73). (**B**) Linear relation between skeletal $\delta^{18}O$ and temperature in *Pavona clavus* along the 6 and 12 mm/year growth transects. The regression lines are $[\delta^{18}O]_{6\ \mathrm{mm/year}} = 0.22 - 0.174T$ (r = 0.82) and $[\delta^{18}O]_{12\ \mathrm{mm/year}} = -1.56 - 0.106T$ (r = 0.84). The insets illustrate the differential variation in Sr/Ca (A) and $\delta^{18}O$ (B) along the growth transects as a function of time. The significance of the offset between transects is evident in a comparison with the measurement precision indicated on the 12 mm/year transect ($\pm 2\sigma$ for Sr/Ca and $\pm 1\sigma$ for $\delta^{18}O$).

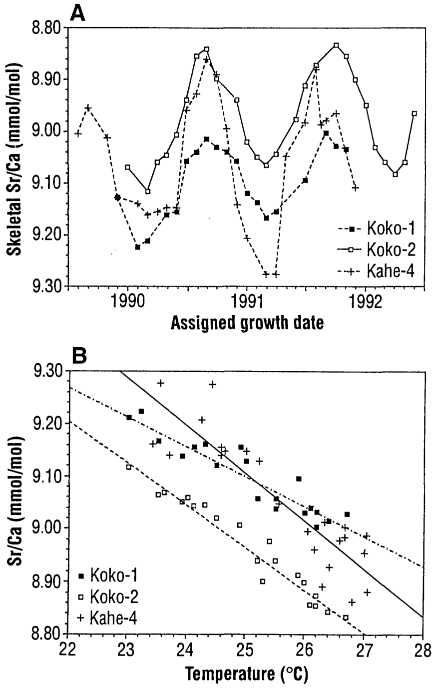

Fig. 2. (**A**) Seasonal variations in skeletal Sr/Ca of three Hawaiian *Porites lobata* specimens from Koko Head, Oahu (Koko-1 and Koko-2) and Kahe Point, Oahu (Kahe-4). (**B**) Sr/Ca-temperature relation established for each of the *Porites lobata* specimens on the basis of the SST record at each sampling site. The regression lines are $[\mathrm{Sr/Ca}]_{\text{Koko-1}} = 10.52 - 0.0569T$ (r = 0.97), $[\mathrm{Sr/Ca}]_{\text{Koko-2}} = 10.96 - 0.0795T$ (r = 0.99), and $[\mathrm{Sr/Ca}]_{\text{Kahe-4}} = 11.36 - 0.0904T$ (r = 0.95).

bolic activity of the coral is subject not only to temperature but to changes in factors such as light intensity, sea level, turbidity, and nutrient supply (*17*). Environmental stress resulting from a change in any of these factors may produce slower extension and calcification rates (*17*), which would imply enriched skeletal Sr/Ca values or apparently colder LGM temperatures. If suboptimal growth conditions prevailed during glacial-interglacial transitions and resulted in enhanced skeletal Sr/Ca uptake, the Sr/Ca thermometer may overestimate the real SST change. Our results suggest that unless these effects are understood to an extent that would allow a retrospective assessment of their magnitude in fossil corals, coralline Sr/Ca values cannot be considered an absolute proxy of past SST variations.

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Temperature Measurements of Shock-Compressed Liquid Hydrogen: Implications for the Interior of Jupiter

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Shock temperatures of hydrogen up to 5200 kelvin were measured optically at pressures up to 83 gigapascals (830 kilobars). At highest pressures, the measured temperatures are substantially lower than predicted. These lower temperatures are caused by a continuous dissociative phase transition above 20 gigapascals. Because hydrogen is in thermal equilibrium in shock-compression experiments, the theory derived from the shock data can be applied to Jupiter. The planet's molecular envelope is cooler and has much less temperature variation than previously believed. The continuous dissociative phase transition suggests that there is no sharp boundary between Jupiter's molecular mantle and its metallic core. A possible convectively quiescent boundary layer might induce an additional layer in the molecular region, as has been predicted.

Jupiter, the largest planet in the solar system, has long been of considerable interest to astronomers. This planet is composed primarily of hydrogen with about 10 atomic % helium; the interior is at high pressures (P) and high temperatures (T) because of the large mass and low thermal conductivity (*1*). For example, the boundary between the molecular hydrogen mantle and the metallic hydrogen core is estimated to be 300 GPa (3 Mbar) and 10,000 K at 0.77 of Jupiter's radius (*2*). Pressures and temperatures at the center range up to 4 TPa and 20,000 K. Conditions in planetary interiors are calculated from theoretical models that are consistent with the observed mass, radius, rotational rate, gravitational moments, and surface chemical composition. Density (ρ) distributions are calculated from the gravitational moments, which are very sensitive to the equation of state at very high pressures and temperatures (*3*). Because the internal temperatures are well above the calculated melting curve of hydrogen, Jupiter is in the fluid phase (*4*); the interior is assumed to be fully convective and adiabatic and to obey an isentropic equation of state. Here, we report shock temperature measurements of liquid hydrogen and their implications for the nature of the interior of Jupiter.

Shock-compression measurements of the equations of state of hydrogen and helium

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