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High-Resolution Spectroscopy of the Earth's Free Oscillations, Knowing the Earthquake Source Mechanism

Abstract. *A new method for identification of normal modes of oscillation of the earth yielded unambiguous determinations of many overtones never before identified. This method consists of the superposition of spectra observed at many stations over the earth, after a correction for the phase determined from the known earthquake source mechanism.*

After a large earthquake, such as the Alaskan earthquake of 28 March 1964, the earth continues to vibrate for days or even weeks. These vibrations consist of a superposition of the infinite number of normal modes of oscillation of the earth; the determination of the eigenfrequency corresponding to each mode is of great importance in revealing the properties of the earth's interior. Each mode manifests itself as a sharp peak in the ground displacement spectrum as observed at a seismological station. The identification of a peak in such a spectrum as corresponding to a given mode is relatively simple for the low-frequency range, where only the lower overtones exist and the peaks are well separated from each other. The usual method of identifying a peak consists of matching theoretical to observed eigenfrequencies, complemented by some additional criteria (*1*). For higher frequencies the separation between peaks becomes smaller, and in general for periods below 250 seconds the peaks can not be unambiguously identified by the usual methods.

Here I report a new method of identification, the excitation criterion. It requires a knowledge of the source mechanism of the earthquake exciting the free oscillations, and it is necessary to have observations from many seismographs all over the earth. The method consists of the following steps. First the theoretical amplitude and phase are computed at all the observing stations for the mode to be identified, say, the mode ${}_5S_{26}$, as excited by a double couple model of the earthquake, with its geometry determined from the first motion of *P* waves, in a realistic spherically symmetric model of the earth (*2*). I assumed a step function as source time function. For wavelengths much longer than the dimensions of the earthquake fault the theoretical phase of a spectral peak can only be 0 or π (*3*). A factor of π is then added to the phase of the observed spectra at those stations where the theoretical phase of ${}_5S_{26}$ is π, leaving the spectra at all other stations unchanged. With this correction the phase of ${}_5S_{26}$ will be the same at all the observing stations, while for other modes the phase will be π at some stations and 0 at others. Finally, all the spectra are vectorially added. Through this summation the peaks of ${}_5S_{26}$ will add constructively because they have

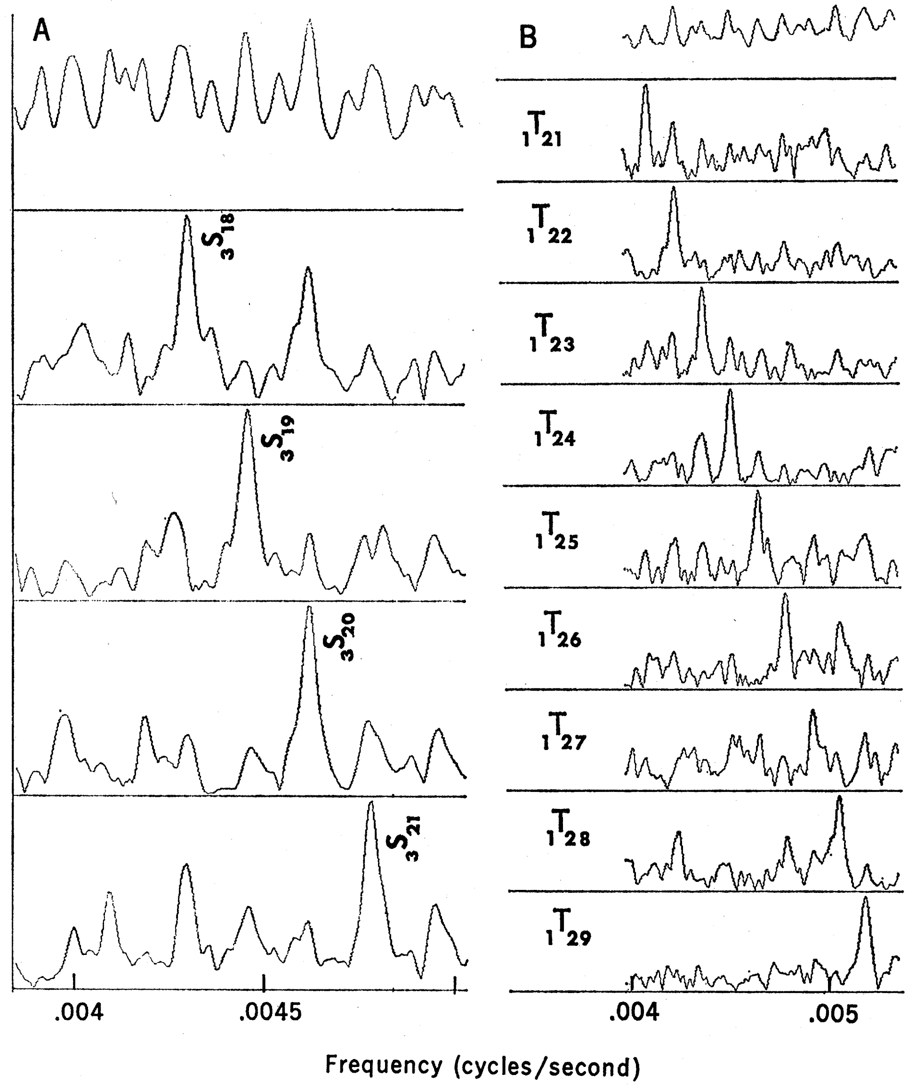

Fig. 1. Examples of identification of spectral peaks for the third higher spheroidal modes ${}_3S$ in the colatitudinal component (A), and the first higher torsional modes ${}_1T$ in the azimuthal component (B). The spectra at the top are the sums of the absolute amplitudes of the spectra at all the stations. The remaining spectra are the result of using the excitation criterion to identify spectral peaks.

the same phase at all stations, while the peaks of all other modes cancel each other because their phase is more or less randomly divided between 0 and π. If properly excited, ${}_5S_{26}$ should dominate the summed spectrum, and if the stations are uniformly distributed over the earth the frequency thus determined will be the average frequency corresponding to the degenerate eigenfrequency of an ideal unperturbed spherically symmetric earth model (*4*).

The excitation criterion was successfully applied to identify spectral peaks of oscillations excited by the deep shock which occurred on 31 July 1970 in southern Colombia, at a depth of 651 km. This event was not followed by aftershocks that would complicate the radiation pattern. The close agreement between the theoretical and observed spectra at single stations for the fundamental spheroidal modes between 170 and 600 seconds supports the assumption that the source mechanism derived from *P* waves is valid for long-period oscillations.

Spectra from 83 stations were used in this case. In order to increase the signal-to-noise ratio, I did not use spectra from stations where the theoretical amplitude of the peak to be identified was less than half the average amplitude over all the stations, since adding these spectra merely increases the noise in the summed spectrum. Some of the peaks that have been identified are shown in Fig. 1. These new data will impose strong constraints on earth models in the future.

The excitation criterion not only identifies unambiguously the spectral peaks but also enhances the signal-to-noise ratio. It is successful even for modes with low values of the parameter *Q* (high attenuation) and at frequencies where the spectral peaks are very close to each other. The resulting identifications are not biased by personal judgment, and the method is not critically dependent on the earth model used to compute the theoretical amplitudes. An extension of this technique would be to sum the spectra of many earthquakes after applying the proper correction to the phase.

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Unisexual Fish: Laboratory Synthesis of a "Species"

Abstract. *By hybridizing bisexual (gonochoristic) fishes, all-female clones have been produced that are comparable to those of a wild unisexual "species,"* Poeciliopsis monacha-lucida, *living in northwestern Mexico. The laboratory unisexuals have consistently given birth only to female progeny for six generations.*

Unisexual "species" are known from no fewer than nine genera of cold-blooded vertebrates. Morphological, cytological, and biochemical studies have demonstrated that most of these are of hybrid origin (*1, 2*). Although parental precursors have been identified for several all-female vertebrates, until now none have been synthesized in the laboratory. Among the lizards, where the greatest number of all-female "species" occurs, rearing difficulties limit the amount of experimental manipulation possible. The same is true of *Ambystoma*, the only genus of amphibians with unisexual representatives.

In fishes, however, only three genera contain unisexuals; all are readily cultured. Hubbs and Hubbs (*3*) experimented for 15 years with *Poecilia formosa*, the first all-female "species" to be discovered. Although its parental origin was determined, they were unable to synthesize it. Apparently, no attempts have been made to trace the origin or to synthesize the unisexual goldfish, *Carassius auratus*, that occurs in Russia and Japan (*4*).

The third genus with all-female representatives is *Poeciliopsis*, which, like *Poecilia formosa*, is a live-bearer (family Poeciliidae). Included in this genus are three diploid and three triploid unisexual forms, all from northwestern Mexico (*2*). This report concerns one of the diploids, *Poeciliopsis monacha-lucida*, which is postulated to be an evolutionary stepping-stone to the other five (*5*). Morphological, experimental, and ecological evidence gathered for 17 years indicates that this fish arose as a *P. monacha* × *P. lucida* hybrid in the Río Fuerte of Sinaloa, Mexico.

The evolutionary events that produced and now sustain this unique all-female "species" are as follows. In one of the narrow zones where the ranges of the parental species overlap, *P. monacha* females crossed with *P. lucida* males, giving rise to the morphologically intermediate form *P. monacha-lucida*. Because the sex-determining mechanism of *P. monacha* is "stronger" than that of *P. lucida*, such hybrids are exclusively females. Within the hybrid, random segregation of maternal and paternal chromosomes does not occur. Although the possibility exists for an occasional *P. lucida* chromosome to be transmitted to the egg (*6*), genetic evidence indicates that only those of *P. monacha* survive oogenesis (*7*). In this manner the "strength" of the maternal genome is held intact through successive generations, and unisexuality is preserved in each union with the "weaker" *P. lucida* sperm. Elimination of paternal chromosomes occurs in the mitotic divisions preceding meiosis. A single set of chromosomes, presumably *P. monacha*, becomes associated with a unipolar spindle. The other set, presumably the paternal complement, remains scattered in the cytoplasm. At anaphase, the maternal (*P. monacha*) chromosomes are clustered at the single pole, where they become surrounded by the reconstituted nuclear membrane; whereas the paternal (*P. lucida*) chromosomes are either absorbed or expelled in the fashion of a polar body (*6*). Meiosis apparently consists of a single equational division, which eliminates crossing-over or random segregation as a path for introgression of paternal elements. After 27 generations, laboratory strains of *P. monacha-lucida*, originally collected from the Río Fuerte in 1961, still produce only female offspring by their *P. lucida* mates. This unique mode of reproduction has been termed "hybridogenesis" (*5*).

More than 67 matings of *P. monacha* with *P. lucida* have been attempted since 1957; five were successful in the sense of providing fertile offspring that survived to maturity. Difficulties with this cross derive mainly from a disparity in size between the hybrid embryo and