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Jovian Seismology

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Standing acoustic waves, with periods between about 4.5 and 9 min, may be trapped in a wave duct beneath Jupiter's tropopause. Detection of these oscillations by observations of Doppler shifting of infrared and ultraviolet absorption lines would offer a new and important method for probing the giant planet's deep atmosphere and interior. Information would be revealed on Jupiter's thermal and density structure and the depth to which its zonal winds penetrate. Standing oscillations in the molecular hydrogen envelope are modeled and their theoretical eigenfrequencies are presented as they might appear in actual data analysis. Several forcing functions for wave generation are considered. These include coupling with turbulent and convective motions, thermal overstability due to radiative transfer, effects of wave propagation in a saturated atmosphere, and consequences of *ortho*- to *para*hydrogen conversion. Although the forcing mechanisms couple well with the acoustic waves, allowing for possible maintenance of the oscillations, the contribution they make to velocity amplitudes is very small, between 1.0 and 0.1 m sec^{-1}. This implies that the Doppler shifting caused by the waves may be unresolvable except, perhaps, by methods of superposing time records of oscillations to enhance acoustic signals and diminish random noise.

1. INTRODUCTION

Helioseismology, the study of the Sun's interior using acoustic waves as a probe (Deubner and Gough, 1984; Christensen-Dalsgaard *et al.*, 1985a), has been enormously successful in revealing information on solar structure ever since the detection of the solar 5-min oscillations (Leighton *et al.*, 1962) and their identification as standing acoustic waves trapped in a waveguide beneath the photosphere (Ulrich, 1970; Leibacher and Stein, 1971). The waveguide is manifest as the superposition of global spherical harmonic oscillations, the radial velocities of which Doppler shift visible light emanating from the photosphere. The frequency shifts allow the surface spherical harmonic pattern to be resolved in both space and time. The resulting data reveal information on the thermal structure and rotation of the Sun's interior.

In this paper, we propose that a similar trapping of acoustic waves is likely to occur below Jupiter's tropopause. The detection of such short-period, high-degree oscillations would signify the advent of Jovian seismology as a new observational technique for probing the interior of the giant planet. The acoustic waves confined to the Jovian waveguide are distinct from the long-period (20–140 min), low-degree, free oscillations of Jupiter (Vorontsov *et al.*, 1976; Vorontsov and Zharkov, 1981; Vorontsov, 1981, 1984a, 1984b) which do not depend on the presence of the cavity.

2. UPPER REFLECTING BOUNDARY

On the Sun, the upper boundary of the wave duct for the 5-min oscillations is essentially determined by the acoustic cutoff frequency ω_a. An upward propagating wave impinging on a layer with a given ω_a will either reflect away from that layer if its frequency is less than ω_a or propagate through the layer if its frequency is greater than ω_a. For the Sun, the acoustic cutoff frequency increases abruptly with height beneath the photosphere for two reasons. First, the temperature minimum on the Sun is very sharp and $\omega_a \propto T^{-1/2}$ (T is absolute temperature) (Leibacher and Stein, 1981). Second,

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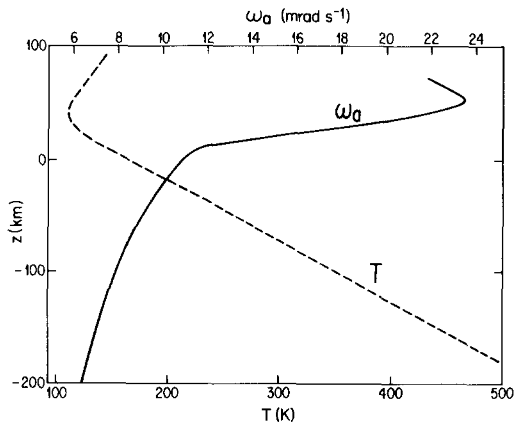

FIG. 1. Jupiter's temperature profile from Orton (1981) and Lindal *et al.* (1981) (dashed curve) and the corresponding profile of acoustic cutoff frequency (solid curve). Zero altitude is at the 1-bar level. This model assumes a mass fraction of 0.888 H_2, 0.112 He, 1.7×10^{-3} CH_4, and 2.2×10^{-4} NH_3.

atomic hydrogen in the convection zone undergoes recombination beneath the photosphere. Thus the mean molecular weight μ changes from 1.0 to 1.4 at the temperature minimum and $\omega_a \propto \mu^{1/2}$ (R. K. Ulrich, private communication). Therefore, ω_a increases abruptly with height over just a few scale heights. This creates a distinct broadband (in frequency) reflecting layer for upward propagating waves with periods longer than about 3 min (Deubner, 1981).

Though the temperature minimum on Jupiter is not as sharp as on the Sun, the acoustic cutoff frequency nevertheless changes rapidly with height at the tropopause (Fig. 1). The relation for ω_a in a nonisothermal atmosphere is (Beer, 1974)

$$\omega_a = \frac{c^2}{4H^2} + \frac{\gamma g}{2T}\frac{\partial T}{\partial z}, \qquad (1)$$

where c = sound speed, H = density scale height, γ = ratio of specific heats, g = gravitational acceleration, z = height, and $\partial T/\partial z$ is the ambient temperature gradient. Equation (1) is valid only if the temperature variation with height is gradual enough that the derivatives $\partial^2 T/\partial z^2$ and $(\partial T/\partial z)^2$ are negligible (Beer, 1974, p. 65); these second-order terms are between three and eight orders of magnitude smaller than $\partial T/\partial z$ in the region of interest, rendering (1) sufficiently accurate. As the temperature gradient in Jupiter's atmosphere changes from adiabatic to isothermal in less than two scale heights (with increasing z just below the tropopause), ω_a goes from approximately $\gamma g/3c$ to $\gamma g/2c$ (Fig. 1). Because of this abrupt increase in ω_a, all upward propagting waves with periods between 4.5 and 9 min will be reflected within approximately two scale heights at the tropopause.

Early helioseismological models used the isothermal acoustic cutoff frequency, which corresponds to the first term on the right of (1). This term increases sharply just as the Sun's temperature minimum is approached from below through a very superadiabatic region. However, the second term becomes strongly negative in this same region, thereby diminishing, if not canceling, the increase in ω_a due to the isothermal term. The broadband acoustic mirror beneath the photosphere is not due so much to the sharp, steplike temperature decrease, but to the thermal gradient transitioning from superadiabatic to isothermal within approximately one scale height at the temperature minimum. In this region, the second term on the right of (1) changes from a large negative value to zero, causing ω_a to increase abruptly over a relatively short distance (cf. Christensen-Dalsgaard, 1986).

3. LOWER REFLECTING BOUNDARY

The lower reflecting boundary of the wave duct is determined by the dispersion relation (Leibacher and Stein, 1981)

$$k_v^2 = \frac{\omega^2}{c^2} - \frac{l(l+1)}{r^2}, \qquad (2)$$

where k_v is the vertical wavenumber, ω is the angular frequency, l is the spherical harmonic degree of the free oscillations, and r is the radius. A wave will refract upward (Snell's law) as it propagates obliquely

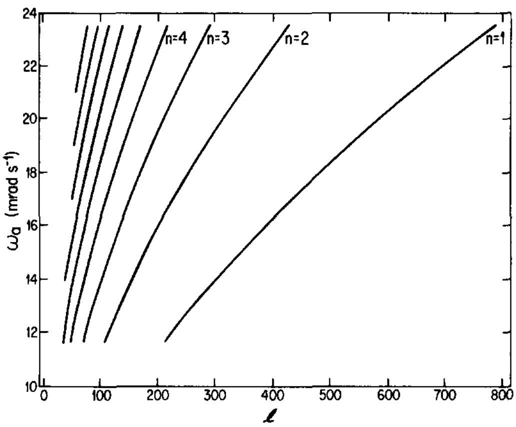

FIG. 2. Theoretical eigenfrequencies of standing waves versus spherical harmonic degree l. n is the radial order of the standing oscillations.

downward through a region of increasing temperature. The lower boundary of the waveguide occurs where the wave refracts to a completely horizontal wave, i.e., where k_v is zero. Thus, the radial location (from the planet's center) of the lower reflecting boundary R_b can be calculated from (2) for a given ω and l. A standing wave occurs when half of the vertical wavelength fits an integer number of times between the upper and lower reflecting radii of the wave duct, or when (Christensen-Dalsgaard *et al.*, 1985b)

$$\int_{R_b}^{R_t} k_v \, dr = \int_{R_b}^{R_t} \left(\frac{\omega^2}{c^2(r)} - \frac{l(l+1)}{r^2} \right)^{1/2} dr = (n + \alpha)\pi, \quad (3)$$

where R_t is the radius of the tropopause, n is the radial order of the standing wave mode, and α is a phase term due to wave attenuation in the vicinity of the temperature minimum at $r = R_t$. For the Sun, α is empirically determined to be approximately 1.58 (Christensen-Dalsgaard *et al.*, 1985b). The attenuation of acoustic waves near Jupiter's tropopause is unknown. Thus, the upper boundary in this model is assumed to be a perfect reflector, and α is equated to zero.

Calculation of n for values of ω and l gives the eigenfrequencies of standing oscillations for waves reflected at the tropopause (Fig. 2). For any value of R_b, ω/l is uniquely determined by (2) (for large enough l), and n/l in turn is uniquely specified by (3). For large l, the curves of Fig. 2 can be reduced to a single curve of R_b vs n/l (Fig. 3). Thus, because each mode of oscillation corresponds to a specific reflection level, depth profiles of sound speed or temperature can be generated.

We have considered only those waves that do not penetrate below the molecular hydrogen–metallic hydrogen interface at approximately $0.78R_J$ (R_J is Jupiter's radius). We used a single equation of state to model the molecular hydrogen envelope; use of piecewise equations of state (e.g., from the ideal gas to the virial to the liquid equation) would incur spurious reflections. The equation we used is dominated by ideal gas behavior at radii near $1R_J$, and, at radii near $0.78R_J$, it becomes representative of a polytrope of index 1 (Hubbard and Horedt, 1983; D. J. Stevenson, private communication):

$$P = K\rho^2 + \rho RT, \quad (4)$$

where P = pressure, ρ = density, R = gas constant for molecular hydrogen, and K is chosen to fit the pressure (~3 Mbar), density (~1000 kg m^{-3}), and temperature (10^4°K) at the molecular–metallic hydrogen interface (Stevenson and Salpeter, 1976).

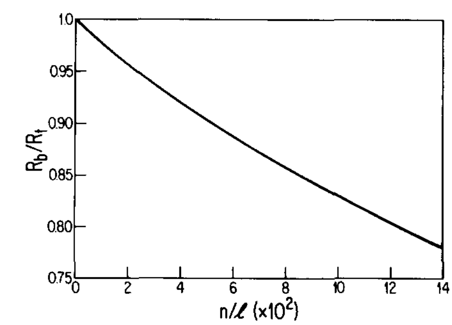

FIG. 3. Ratio of the radius R_b of the lower reflecting boundary of the wave duct to the radius R_t of the tropopause versus n/l.

The temperature $T(z)$ was assumed to follow an adiabat and $\rho(z)$ was determined from (4) and the hydrostatic equation.

It might also be possible to observe waves that refract along the molecular–metallic hydrogen interface, or, for harmonics of low-degree l, waves that penetrate Jupiter's deeper interior. The order of the molecular–metallic phase change is not yet known, although it is suspected to be first order (Stevenson and Salpeter, 1976, 1977). The equation of state for metallic hydrogen is similar in form to (4) (Stevenson, 1975), yet there is probably a 25% increase in density across the equilibrium boundary (Ross, 1974; Ross and McMahan, 1976). Thus, reflections are expected to occur from the molecular–metallic hydrogen interface leading to sharp discontinuities in the eigenfrequency curves.

4. ROTATION AND ZONAL WINDS

The calculation of frequency ω solely in terms of degree l and radial order n assumes spherical symmetry. Though rotation imposes a special direction thereby breaking the assumed symmetry, the oscillations can still be modeled as spherical harmonics provided the polar coordinate axis is the rotation axis. In this case ω depends on azimuthal order m as well as on l and n. When $m \neq 0$ (i.e., sectoral ($m = l$) and tesseral ($m < l$) harmonics), spherical harmonic oscillations rotate with the planet and their apparent frequencies, as measured in an Earth-based or inertial frame, are shifted. Zonal harmonics ($m = 0$) are unaffected by rotation. Zonal winds present a further complication. Their directions are functions of latitude, with several wind systems reversing sign from one latitude to another. Hence, Jupiter's rotation cannot be modeled as solid body rotation.

Frequency splitting of oscillations can provide information on the depth dependence of rotation and wind velocity (Duvall and Harvey, 1984; Duvall *et al.*, 1984). The frequency splitting is defined as

$$\omega'(n, l) \equiv \frac{\omega(n, l, m = -j) - \omega(n, l, m = +j)}{2j}, \quad (5)$$

where j is an integer $\leq l$. The sign of j determines whether the azimuthal component of the wave is prograde ($m = -j$) or retrograde ($m = +j$). If Jupiter rotated as a solid body, $\omega'(n, l)$ would be its angular rotation frequency. Since the depth at which acoustic waves reflect is determined by n and l, $\omega'(n, l)$ will measure the angular frequency of the planet at different depths. Because of the zonal winds, sectoral modes should be avoided. Tesseral modes with latitudinal structure equal to or finer than the zonal wind structure will need to be used to determine variations in jet structure with depth.

The presence of zonal winds also implies the existence of a critical layer for waves whose azimuthal wavenumber k_x is antiparallel to a jet (Beer, 1974). The critical layer is a level at which waves whose wind-shifted frequencies approach zero are attenuated. At the critical level $\omega \rightarrow U_0 k_x$, where U_0 is the wind speed. Since $k_x = m/r$ (r is radial distance from Jupiter's center), U_0 is between 10 and 80 m sec^{-1} (Ingersoll *et al.*, 1979), ω is between 11.7 and 23.5 mrad sec^{-1}, and r is between $1R_J$ and $0.78R_J$, m will need to be on the order of 10^4 to 10^5 for a critical layer to affect reflections at the tropopause.

6. FORCING MECHANISMS

One of the most important but least understood aspects of free oscillations in the Sun is the forcing mechanism that drives the standing waves. For the waves to be significant probes of the body's interior, they must be sustained for at least several oscillation periods. This necessitates a net influx of energy into the oscillatory motions that can allow the waves to overcome dissipative effects and maintain wave amplitudes large enough to induce observable Doppler shifts.

Forcing of the 5-min oscillations on the Sun may occur through a coupling of the acoustic waves with turbulent convective motions. Calculations show that such a mechanism could supply enough energy to the waves (Antia *et al.*, 1984) but the frequencies of turbulent or convective turnover are not commensurate with the 5-min oscillations, thereby preventing strong coupling (R. K. Ulrich, private communication). On Jupiter, the opposite may be true. For eddy (or convective) velocities between 10 and 80 m $\sec^{-1}$ and length scales on the order of a scale height (~20 km at the 1-bar level), the periods of turbulent motions match well with the standing wave periods (4.5–9 min).

Though the frequencies of Jovian turbulence and acoustic modes may be comparable, Jovian turbulence can support an acoustic wave field of only limited amplitude. The power per unit volume supplied to an acoustic wave by the decay of a turbulent eddy is (Stein and Leibacher, 1981).

$$W = \frac{\rho u^3}{\lambda} (k\lambda)^{2n'+1}, \tag{6}$$

where ρ = gas density, u = eddy velocity, λ = eddy wavelength, k = acoustic wavenumber, and n' determines the multipole character of the energy source. A monopole ($n' = 0$) implies a mass source or sink which is not significant for the Sun or Jupiter. Dipole emission ($n' = 1$) corresponds to a momentum source, i.e., flow due to an external force or pressure gradient; a quadrupole source ($n' = 2$) applies to nonlinear forces such as turbulent Reynolds stresses. On the Sun, dipole emission is insignificant (Stein and Leibacher, 1981). However, this might not be the case for Jupiter. Reynolds stresses are probably as important on Jupiter as on the Sun. Therefore, both $n' = 1$ and $n' = 2$ should be considered for Jupiter. Since coupling of eddy motions and acoustic waves requires their frequencies to be equal, $kc = u/\lambda$, and therefore $k\lambda = u/c$ is the Mach number M. Thus, the power radiated by turbulence into acoustic waves is

$$W = \frac{\rho u^3}{\lambda} (M^3 + M^5). \tag{7}$$

By equating the energy flow from turbulence $W\lambda$ to the acoustic energy flow $\rho c u_0^2$ (Lighthill, 1979), one can assess the contribution made by turbulence to the magnitude u_0 of the acoustic wave field. For Jupiter, $\rho \simeq 0.1$ kg m^{-3}, $u \leq 80$ m $\sec^{-1}$, λ = scale height $\simeq 20$ km, $c \simeq 1$ km $\sec^{-1}$, and u_0 is found to be ≤ 0.5 m $\sec^{-1}$. This is small compared to the approximately 500 m $\sec^{-1}$ radial velocities that produce the Doppler shifts observed on the Sun. This forcing mechanism may be highly significant for Saturn because the Mach number of its equatorial jet is very nearly unity as compared with 0.08 for Jupiter's equatorial jet.

Thermal overstability provides another possible mode of forcing. Overstability refers to oscillations whose amplitudes grow with time. In the Sun, acoustic waves can become overstable by a process known as the Eddington Valve (Stein and Leibacher, 1981). When a parcel of gas undergoing acoustic oscillations compresses nearly adiabatically, it becomes hotter and the opacity increases, allowing for greater absorption of radiation. The enhanced accumulation of heat raises the pressure and the subsequent expansion will be stronger than if the process was purely adiabatic. Thus, the transfer of radiative to mechanical energy causes the amplitudes of the waves to grow. However, the growth rate for the waves is very small and growth will only be significant if there is balance between energy influx from turbulence and dissipation from turbulence (Stein and Leibacher, 1981). This mechanism is virtually negligible for Jupiter since its specific luminosity (power output per unit mass), which directly determines radiative energy flow, is six orders of magnitude smaller than the Sun's (Hubbard, 1984).

Jupiter's troposphere contains many constituents, several of which, especially water, ammonium hydrosulfide, and ammonia, undergo condensation at various levels. The effects of a saturated atmosphere on the progagation of internal gravity waves has been examined by Einaudi and Lalas (1973, 1975). The effects of the latent heat of condensation on acoustic waves may be understood by considering a wave propagating upward toward a saturated layer. If, just below the condensation level, an oscillating parcel of gas adiabatically expands such that the resulting temperature drop induces condensation and a release of latent heat, then the subsequent expansion is strengthened and the wave amplitude is magnified. However, the enhancement of the oscillation amplitude will be lost when adiabatic compression of a gas parcel above the condensation level triggers vaporization and absorption of latent heat, effectively canceling the newly gained mechanical energy. This could happen, for small wavelengths, after the wave passes through the condensation level, or, for longer wavelengths, after the wave reflects at the tropopause and passes downward through the cloud deck. Therefore, there is no net flow of energy into the oscillations, hence no growth of wave amplitudes.

Nonequilibrated constituents of the atmosphere may offer a source of energy to acoustic waves without the equivalent sink. An example of this occurs with Jupiter's major constituent, hydrogen. At high temperatures ($T > 200°$K), hydrogen is comprised of 75% *ortho*hydrogen (where the two protons of the molecule have parallel spins) and 25% *para*hydrogen (antiparallel spins). As temperature approaches zero, the equilibrium composition of the gas goes to 100% *para*hydrogen. However, the transition from *ortho-* to *para*hydrogen is very slow. If equilibration at low temperatures is slower than or of the same rate as convective overturn, then considerable disequilibrium would be expected in Jupiter's upper atmosphere; this is in fact indicated by Voyager infrared data (Gierasch, 1983; Conrath and Gierasch, 1984). Since equilibration from *ortho-* to *para*hydrogen involves an exothermic reaction, a considerable source of energy is available in the metastable *ortho*hydrogen. However, as stated above, the reaction is exceedingly slow and requires catalysts (e.g., free radical surface sights of aerosol particles, H_2–H_2 *para*magnetic interactions, etc.) to be of any dynamical significance (Massie and Hunten, 1982; Gierasch, 1983; Conrath and Gierasch, 1984).

The reaction rates of most catalysts depend on the molecular collision velocity which goes as $T^{1/2}$; thus, the rate of *ortho–para* conversion increases with temperature. Accordingly, an oscillating parcel of gas may equilibrate faster when adiabatically compressed (increasing the parcel's temperature), and the subsequent release of latent heat will cause a stronger expansion. The equivalent absorption of latent heat will not occur since the *para–ortho* conversion would only take place in regions of higher temperature where equilibrium is already established and there is no need for conversion. Therefore since there is only a source of energy for the oscillations, the acoustic waves could be overstable.

For this mechanism to be significant, the rate of wave growth must be relatively fast to overcome dissipation. The fractional change in volume V with time for an ideal gas at constant pressure is

$$\frac{1}{V}\frac{\partial V}{\partial t} = -\frac{1}{T}\frac{\partial T}{\partial t}. \tag{8}$$

The change in enthalpy at constant pressure due to the release of latent heat in the compression phase of the oscillation yields an expression for the rate of change of temperature

$$\frac{\partial T}{\partial t} = \frac{\chi L}{c_p}\frac{\omega}{\pi}, \tag{9}$$

where χ is the ratio of the mass of converting *ortho*hydrogen to that of total hydrogen, L is the latent heat of conversion, and c_p is the specific heat capacity at constant pressure. Volume perturbations therefore grow approximately as

$$V \propto \exp\left(\frac{\chi L \omega}{T_0 c_p \pi}\, t\right), \tag{10}$$

where T_0 is the ambient temperature. The growth time is $(c_pT_0/2\chi L) \cdot t_p$, where t_p is the oscillation period. At $T_0 = 130°K$, $L = (230°K) \cdot R$ (Massie and Hunten, 1982), and $(c_pT_0/2L)$ is 0(1). The controlling factor is χ. The equilibration time constant ν_e is about 10^{-9} sec^{-1} (Conrath and Gierasch, 1984), so that after an oscillation period between 250 and 600 sec, $10^{-7} < \chi < 10^{-6}$, implying a growth time that is greater than 10^6 oscillation periods, or about 10 years. Unless dissipative effects are well balanced by other forcing mechanisms, this growth mechanism is more than likely insignificant.

7. OBSERVATIONS

Standing waves on the Sun occur just below the photosphere, causing it to oscillate with the wave motions. Therefore, the frequency and spherical harmonic degree of the oscillations can be determined from the Doppler shifting of visible light absorption bands by the radial velocity of the oscillations. On Jupiter, the oscillating layer is the tropopause and infrared radiation corresponding to temperatures at the tropopause might reveal Doppler shifting in a spherical harmonic pattern. There are also absorption bands of UV and IR radiation which occur near the tropopause. Methane absorbs at 7.8 μm near the 145°K level above the tropopause (Wallace, 1976; Wagener *et al.*, 1985). Ammonia has several distinct absorption bands between 0.16 and 0.24 μm at the tropopause (Wagener *et al.*, 1985; Prinn and Owen, 1976).

The best candidate for UV absorption is also one of the most controversial. Directly above the tropopause is a haze which absorbs near-UV radiation around 0.3 μm (Greenspan and Owen, 1967). However, the composition of the layer is still uncertain. Several models (Prinn and Owen, 1976; Strobel, 1973; Visconti, 1981) suggest that the haze is comprised of hydrazine (N_2H_4) crystals which are opaque to 0.3 μm UV. Other studies (Wagener *et al.*, 1985; Sato and Hansen, 1979; Cochran and Slavsky, 1979) conclude that hydrazine cannot be a major constituent of the haze because it is doubtful that NH_3 or N_2 could ever penetrate into the stratosphere from the troposphere to form hydrazine. Compounds formed by photodissociation of CH_4 and H_2 (Cochran and Slavsky, 1979) have, instead, been proposed to comprise the haze.

Long-period observations over Jupiter's disk of Doppler shifting in emitted radiation and/or absorption bands may reveal information on the eigenfrequencies and harmonic degree of trapped acoustic waves. Although UV measurements may need to wait for the Hubble Space Telescope, high-resolution IR measurements may be obtained by use of heterodyne spectroscopy (Mumma *et al.*, 1975).

(Recent attempts have been made to observe motions in Jupiter's atmosphere using reflected sunlight at a visible wavelength (0.63 μm). Although motions with velocities on the order of 100 m sec^{-1} were detected, power spectra were more indicative of random noise than of coherent oscillations (C. Pilachowski, personal communication).)

8. DISCUSSION

There is little doubt that Jupiter's dynamic atmosphere can generate internal waves. The greatest question is whether forcing mechanisms are present which allow for the growth and maintanence of large radial velocities. No matter what forcing mechanism one can imagine, it remains a fact that the Sun's specific power output is six orders of magnitude greater than Jupiter's and specific power represents the amount of energy flux that the acoustic waves can draw upon. Since acoustic energy flow goes as the square of the velocity amplitude (Lighthill, 1979), the velocity amplitudes are at best three orders of magnitude smaller on Jupiter than on the Sun.

This difficulty may be assuaged with an adaptation of the method of "stacking" used by exploration seismologists. Superposition of seismic records (i.e., travel time records of incoming signals), using a known acoustic signal as a pivot, allows regular signals to become enhanced while random noise tends to cancel out. Since exploration seismologists supply the semismic source, they maintain a luxury which Jovian seismologists would not share: knowledge of when (and where) the acoustic waves are generated, and hence, exactly how to stack different records.

The task of stacking would be made simpler for a Jovian seismologist if at least one unique, recognizable signal appeared on the time records of Doppler shifting. Considering probable velocity amplitudes of 10^{-1} m $\sec^{-1}$, such a signal would not likely exist. A method of trial and error would need to be employed. For acoustic signals to be enhanced to amplitudes of 10^2 m $\sec^{-1}$, thousands of records will most likely be needed. With the large periods of the waves, a time record would need to be on the order of an hour or more. (One must bear in mind that an oscillation may not persist for the entire length of a record, making the job of stacking even more difficult.) The number of records required, as well as the minimum time needed for each record, present serious limitations for an orbiting telescope. However, were the observations of standing waves to be successful, the field of planetary science would have a unique tool for probing Jupiter's and perhaps the other giant planets' deep atmospheres and interiors.

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