Institute of Sound and Vibration Research

# The Effect of Fluid Loading on the Generation of Extraterrestrial Sound

**T.G. Leighton**

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UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

FLUID DYNAMICS AND ACOUSTICS GROUP

**The Effect of Fluid Loading on the Generation of Extraterrestrial Sound**

by

**T G Leighton**

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Authorized for issue by
Professor R J Astley, Group Chairman

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I am greatly indebted to Prof Chris Morfey for the stimulation he has provided on this topic and to Dr Petculescu for assisting in providing the gas densities for the worlds studied in this report.

# CONTENTS

# ABSTRACT

In recent years increased attention has been paid to the potential uses of acoustics for extraterrestrial exploration. Acoustical instrumentation can be deployed in gas, liquid, or solid media for measurement. This report deals specifically with acoustic sensors in gaseous media. Given the variety of atmospheric conditions that could be encountered in other worlds, and the cost and effort associated with sending sensors to them, it is vital that predictive modelling be done to inform the design of the instrumentation and associated acquisition systems, and for mission planning. To this end, it is important to revisit assumptions which have become embedded in our predictions for acoustics in Earth's atmosphere. This report deals specifically with the issue of fluid loading, and assesses the extent to which the radiation mass associated with immersion of an acoustic source in a gas (an effect which is usually negligible on Earth) affects its resonance frequency.

# LIST OF FIGURES

# LIST OF TABLES

# 1 Introduction

For several years, the study of acoustics has entered into space exploration indirectly, in providing explanations for fluctuations we see in dust clouds in space, or for the giant slow oscillations in the shape or density of planets and stars [1, 2]. However these phenomena do not convey the impression of ‘sound’ to the layperson. Other manifestations of ‘sound from space’ may delight the listener, but in fact have nothing to do with ‘sound’ until played to the listener: they originated and were detected as radio waves, and it is only when they are artificially converted into sound that we hear them. They were never originally sound waves [1, 2].

The vast majority of probes which we have sent to other planets and moons have been ‘deaf’, in that they contained no actual microphones. This is surprising considering the extent to which we use sound to find out about our own environment. Throughout the history of space exploration, an impressive suite of sensors has been launched on probes for extraterrestrial research. However whilst camera systems are almost ubiquitous, most probes have lacked any sensitivity to sound. Whilst acoustic information cannot compete with images for human interpretation, sound in the absence of vision contains complementary information that we often take for granted in many aspects of human life (from diagnosing the performance of machinery a car engine as we drive, to estimating the ferocity of a rainstorm on the bedroom window at night, to monitoring the happiness of a baby hidden beneath the canopy of a pram). Furthermore, acoustic sensors have a number of appealing characteristics for space exploration. They tend to be light, both in terms of weight and in terms of power consumption, both of which are important factors when it comes to the design of space probes where the resources are limited to what the probe can carry. In addition, once the probe has collected information, it has to be transmitted back to Earth, perhaps via link to an orbiter, and this always places constraints on the quality of information that can be transmitted back to Earth. A signal containing sound alone requires less bandwidth than a video.

In our own solar system there is a wealth of environments that we might explore with sound, and some of these are liquid (such as the lakes of Titan [3-7] or the expected subsurface oceans of Europa [4,8-11] and Enceladus [2]). The seismic investigation of planets is well-established.

There is current interest in the use of microphones in atmospheres. In-atmosphere microphones have been deployed on four off-world missions to date. In 1982 the Soviet *Venera* 13 and 14 landers pioneered the use of microphones, initially intended to listen for lightning. What they actually recorded was inconclusive, most of the recorded sounds having been generated by air flow past the lander once it had landed (although subsequently the microphone records were interpreted to estimate wind speeds of 0.35 to 0.57 m/s) [12, 13]. NASA's *Mars Polar Lander* was also equipped with a microphone, but contact was lost with the probe before data could be obtained. In January 2005 the European Space Agency's *Huygens* probe, having 'hitched a 7-year ride' on the NASA's spectacularly successful *Cassini* spacecraft [6,7,14-16], returned microphone records that were the result of turbulent gas flow past the microphone during the parachute descent to the planet through Titan's atmosphere (which, apart from being extremely cold at -178$^{\circ}$C, is in other ways very similar to our own: it contains 95% of nitrogen, and the atmospheric pressure at Titan's surface is just 50% greater than that of Earth's).

The atmospheric microphones used to date on Venus and Titan appear to have been compromised by the dominance over any acoustical signal of aerodynamic pressure fluctuations caused by flow over the sensor and probe. In hindsight this effect might have been mitigated by the use of appropriate windshields, or multiple microphones to distinguish the true acoustical signal from the non-acoustical ones. The only other target for extraterrestrial microphones to date was Mars which, using current models, can be seen to offer few possibilities of detecting audio-frequency sound at distance because of the high absorption there [17]. These observations together emphasize the importance of incorporating predictive acoustical modelling into the planning of missions and the design of probe equipment, because extraterrestrial atmospheres can exhibit characteristics which are unexpected on Earth.

The object of this report is to investigate whether one such characteristic, fluid loading on a sound source, is important in other atmospheres in the Solar System.

# 2 Theory

## 2.1 Background

Sound is most usually generated in a fluid (i.e. a liquid or a gas) through the vibration of a body which is bounded at least partially by an interface with that fluid. This is true, for example, of loudspeakers and the strings, membranes or lips associated with musical instruments. Consider the string of a guitar. To a very close approximation, it vibrates in air in a manner almost distinguishable from the way it would vibrate in a vacuum. There are of course differences in principle: no sound would radiate away from the string through the atmospheric route, and such radiation leads to additional damping, but the effect is usually small in air.

The presence of fluid however affects not just the additional damping, but also to additional inertia. The natural frequency of mechanical oscillators like bells and strings is determined mainly through the ratio of the stiffness of the vibrating system, to the inertia associated with the vibration. The inertia is associated with the momentum of the masses which move when the sound source vibrates. Were a guitar string to vibrate *in vacuo*, then the oscillating string clearly constitutes a moving mass, and so dominates the effective inertia. There is however another contribution to the inertia when the instrument is played in a fluid environment. When the string moves, a volume of fluid is displaced, and this displacement also contributes inertia to the oscillator. For most sound sources in air, this contribution is small, because the density of the atmosphere is low, such that the oscillatory is only slightly different from that which would be found *in vacuo*†. Were instruments to be played underwater, the additional inertia which comes from fluid loading would be greater (indeed, at the opposite extreme of strings operating in air, when a gas bubble underwater pulsates to generate sound, the inertia of the oscillator comes almost

† See comments in Tables 4 to 8.

entirely from the water which is displaced outside the bubble wall as it is displaced, because the density of the gas in the bubble is so low [18, 19]). However the natural frequencies of sound sources which are based on vibrating solids in air (such as most percussion, strings, and loudspeakers) are very similar to those which would occur were the instrument operated in a vacuum (in organs, wind and brass instruments however, vibrations in gas are key to the operation of the source and so the source cannot be discussed without reference to the gas). That is to say, the inertial contribution from fluid loading is usually deemed to be negligible.

The object of this report is to assess whether that assumption holds on other atmospheres that might be encountered in the Solar System.

## 2.2 Radiation impedance

The method will be to undertake example scenario calculations to determine whether the fluid loading contributes significantly to the inertia of the sound source. The examples include the fluid loading for monopole pulsating spheres, for piston sources in tubes, and for vibrating wires.

The assessment will be made using the concept of the radiation impedance of the fluid presented to a given source. Following from the discussion in Section 2.1, the mechanical impedance for a given source can be taken to be the combination of the radiation impedance of the fluid presented to a given source $(Z_{\mathrm{r}})$, and the mechanical impedance of the source radiating in to a vacuum [20]. The real component of the radiation impedance $(Z_{\mathrm{r}})$ is the radiation resistance, $R_{\mathrm{r}}$ (a positive value of which indicates increased dissipation by the source as a result of the presence of the fluid), and the imaginary component is the radiation reactance, $X_{\mathrm{r}}$ (a positive value of which indicates increased mass loading caused by the presence of the fluid, typified by an additional inertia termed the radiation mass, $m_{\mathrm{r}}$).

The following approach is taken from Kinsler *et al.* [20]. If the source were a surface which is with a velocity **u** (which is a function of the position on the surface), then if

$d\mathbf{F}_s$ is the component of the local force in the local direction of motion of the fluid, the radiation impedance of the source is:

$$Z_r = \int \frac{d\mathbf{F}_s}{\mathbf{u}}, \tag{1}$$

where the integral is taken over the whole surface of the source. The importance of the fluid will be shown by comparing the dynamics of the source when it is forced to move in a vacuum (section 2.2(a)), with what happens when the source is moving into a fluid space (section 2.2(b)).

### (a) One-dimensional motion of the face of a rigid source in a vacuum

Consider the one-dimensional problem, where the face of a rigid source of mass *m* and stiffness *s* is driven into uniform rectilinear linear motion by an externally applied harmonic force $F = F_a e^{j\omega t}$ of circular frequency $\omega$. This driving force causes the face to move with speed $u_s = u_{s,a} e^{j\omega t} = j\omega\varepsilon_{s,a} e^{j\omega t}$ where $\varepsilon_s = \varepsilon_{s,a} e^{j\omega t}$ is the displacement of the face. From Newton's Second Law:

$$m\ddot{\varepsilon}_s + R_m \dot{\varepsilon}_s + s\varepsilon_s = F \tag{2}$$
$$\Rightarrow Z_m = F/u_s = F/j\omega\varepsilon_s = jm\omega + R_m - js/\omega.$$
$$\Rightarrow Z_m = R_m + j(m\omega - s/\omega)$$

### (b) One-dimensional motion of the face of a rigid source in a fluid

If the source of section 2.2(a) were now to be driven by an external force to oscillate in fluid as opposed to vacuum, it is now the imbalance between the externally applied force *F* and the force of the fluid on the face (which from Newton's Third Law is equal and opposite to the force $F_s$ exerted by the face on the fluid) which causes the face to move with speed $u_s = u_{s,a} e^{j\omega t} = j\omega\varepsilon_{s,a} e^{j\omega t}$ where $\varepsilon_s = \varepsilon_{s,a} e^{j\omega t}$ is again the displacement of the face. From (1), the force of the fluid on the face is

$$-F_{\mathrm{s}} = -Z_{\mathrm{r}} u_{\mathrm{s}}\,, \tag{3}$$

so that from Newton's Second Law:

$$m\ddot{\varepsilon}_{\mathrm{s}} + R_{\mathrm{m}}\dot{\varepsilon}_{\mathrm{s}} + s\varepsilon_{\mathrm{s}} = F - F_{\mathrm{s}}\,. \tag{4}$$

Replacing the LHS of (4) using (2), and substituting on the RHS of (4) using $-F_{\mathrm{s}} = -Z_{\mathrm{r}} u_{\mathrm{s}}$ (3), gives

$$\begin{aligned} Z_{\mathrm{m}} u_{\mathrm{s}} &= F - Z_{\mathrm{r}} u_{\mathrm{s}} \\ \Rightarrow u_{\mathrm{s}} &= \frac{F}{Z_{\mathrm{m}} + Z_{\mathrm{r}}} \end{aligned}\,. \tag{5}$$

Comparing (4) with (5) shows that the applied force $F$ now encounters exactly the same mechanical impedance of the source as it did *in vacuo* ($Z_{\mathrm{m}}$), plus an additional radiation impedance due to the fluid loading ($Z_{\mathrm{r}}$) [20].

### (c) The complex components of the radiation impedance

The radiation impedance of the fluid-loaded source of Section 2.2(b) can be written to express its complex components (the radiation resistance $R_{\mathrm{r}}$ and the radiation reactance $X_{\mathrm{r}}$) as follows:

$$Z_{\mathrm{r}} = R_{\mathrm{r}} + jX_{\mathrm{r}} = |Z_{\mathrm{r}}| e^{j\theta}\,, \tag{6}$$

where

$$\begin{aligned} \tan\theta &= X_{\mathrm{r}} / R_{\mathrm{r}} \\ |Z_{\mathrm{r}}| &= \sqrt{X_{\mathrm{r}}^2 + R_{\mathrm{r}}^2} \end{aligned}\,. \tag{7}$$

From (5), the input mechanical impedance of the source when it is in a fluid is $Z_{\mathrm{m}} + Z_{\mathrm{r}}$ which from (2) and (6) equals

$$
\begin{aligned}
&Z_{\mathrm{m}} + Z_{\mathrm{r}} = (R_{\mathrm{m}} + j(m\omega - s/\omega)) + (R_{\mathrm{r}} + jX_{\mathrm{r}}) \\
&= (R_{\mathrm{m}} + R_{\mathrm{r}}) + j((m + X_{\mathrm{r}}/\omega)\omega - s/\omega)) \\
&= (R_{\mathrm{m}} + R_{\mathrm{r}}) + j((m + m_{\mathrm{r}})\omega - s/\omega))
\end{aligned}
\tag{8}
$$

which is to say that the inertia of the system has been changed from the *in vacuo* value ($m$) to $(m + m_{\mathrm{r}})$, where the radiation mass is related to the radiation reactance through

$$
m_{\mathrm{r}} = X_{\mathrm{r}}/\omega\,. \tag{9}
$$

If this value is positive, then the resonance frequency of the source is reduced from $(1/2\pi)\sqrt{s/m}$ to $(1/2\pi)\sqrt{s/(m+m_{\mathrm{r}})}$ .

The additional power dissipation in the source caused by the presence of the fluid is

$$
\begin{aligned}
&W_{\mathrm{r}} = \frac{1}{\tau}\int_{t}^{t+\tau} \mathrm{Re}(F_{\mathrm{s}})\,\mathrm{Re}(u_{\mathrm{s}})\mathrm{d}t = \frac{1}{\tau}\int_{t}^{t+\tau} \mathrm{Re}(Z_{\mathrm{r}}u_{\mathrm{s}})\,\mathrm{Re}(u_{\mathrm{s}})\mathrm{d}t \\
&\frac{1}{\tau}\int_{t}^{t+\tau} R_{\mathrm{r}}\,\mathrm{Re}(u_{\mathrm{s}})\,\mathrm{Re}(u_{\mathrm{s}})\mathrm{d}t = \frac{1}{\tau}\int_{t}^{t+\tau} R_{\mathrm{r}}u_{\mathrm{s,a}}^{2}\cos^{2}\omega t\mathrm{d}t \\
&= \frac{1}{\tau}\int_{t}^{t+\tau} \frac{R_{\mathrm{r}}u_{\mathrm{s,a}}^{2}(1+\cos 2\omega t)}{2}\mathrm{d}t \\
&= \frac{u_{\mathrm{s,a}}^{2}R_{\mathrm{r}}}{2}
\end{aligned}
\tag{10}
$$

where the time over which the integration is taken encompasses many oscillatory cycles, and where (3), (6) and the relationship $u_{\mathrm{s}} = u_{\mathrm{s,a}}e^{j\omega t} = u_{\mathrm{s,a}}\cos\omega t + ju_{\mathrm{s,a}}\sin\omega t$ are substituted into the integral.

# 3 Method

As stated earlier, the calculations in this report will assess the influence of some examples of fluid loading on a sound source. Consider a source *in vacuo* of inertia *m* and stiffness *s*. It oscillates *in vacuo* at frequency $f_0$ where:

$$f_0 = (1/2\pi)\sqrt{s/m} \ . \tag{11}$$

If it were now to oscillates in a fluid such that it experience a radiation mass of $m_\mathrm{r}$, then the percentage change caused by fluid loading in the frequency of the source would be:

$$\begin{aligned} \frac{\Delta f}{f_0} \times 100\% &= \frac{\sqrt{s/(m+m_\mathrm{r})} - \sqrt{s/m}}{\sqrt{s/m}} \times 100\% \\ &= \left(\sqrt{m/(m+m_\mathrm{r})} - 1\right) \times 100\% \end{aligned} , \tag{12}$$

In the limit where $m_\mathrm{r} << m$, equation (12) reduces to

$$\frac{\Delta f}{f_0} = \left(1 + \frac{m_\mathrm{r}}{m}\right)^{-\frac{1}{2}} - 1 \approx -\frac{m_\mathrm{r}}{2m} \ . \tag{13}$$

The following subsections will assess the size of this effect for a range of environments and sound sources.

## *3.1 Candidate environments*

The fluid densities on various worlds are investigated. In addition, for comparative purposes, the effect of surrounding source in water at Earth surface standard conditions is shown. In all cases the source is assumed to be surrounded by an infinite homogeneous space containing the fluid in question. Although the densities can vary with latitude and season, for Earth, Venus, Mars and Titan the surface average density at the atmosphere/solid surface boundary is taken as a typical value, as exploration by a lander is not atypical for these worlds.

The situation with the gas giants is more complicated. In the future probes might parachute through these atmospheres, or exploration might occur through dirigible or balloon. Knowledge of the conditions on these planets is currently sufficiently imprecise to provide a wide range of parameter values for the calculations of fluid loading.

The atmospheres of Jupiter and Saturn upper atmosphere is primarily hydrogen (~90%) with some helium (~10%), with trace amounts of other compounds. Uranus and Neptune, in contrast, contain less hydrogen and helium, and more oxygen, carbon, nitrogen, and sulfur, compared to the gas giants Jupiter and Saturn.

Jupiter has a radius of around 70,000 km. It had a dense core of uncertain composition (and this core probably still exists, though this is not certain [21]), surrounded by a 40,000 km-thick layer of liquid metallic hydrogen and some helium which extends out to about 78 percent of the radius of the planet [22]. At the top of this layer of liquid metallic hydrogen the temperature is 10,000 K and the pressure is 200 GPa. Beyond the metallic hydrogen is a 21,000 km-thick layer of liquid hydrogen and gaseous hydrogen, with no sharp boundary between the two, called the interior atmosphere. The clouds (primarily of crystalline ammonia, ammonia hydrosulfide and water) exist at the top of the atmosphere, in a layer which is around 50 km thick, where the atmospheric pressure is 20–200 kPa. The conditions experienced by a probe progressing through these layers vary so greatly that, for the purposes of this study, calculations of the fluid loading is made only for exploration of the atmosphere in conditions that a probe might feasibly survive. Given that the probe will probably have experienced the vacuum of space, and that the survival of exploration vehicles and sensors on Earth is more determined by pressure (and to a lesser extent, temperature) than density, the calculations are made for conditions where pressures are similar to those where engineered probes have survived previously (e.g. Earth's oceans). A maximum pressure of 0.1 GPa (1000 bar) (provided the temperature does not exceed about 100°C) might be seen as a useful starting point for this study (for example, Bosum and Scott cite a maximum temperature of 70°C and a maximum pressure of 85 MPa (850 bar) for their terrestrial seismic sensor [23]).

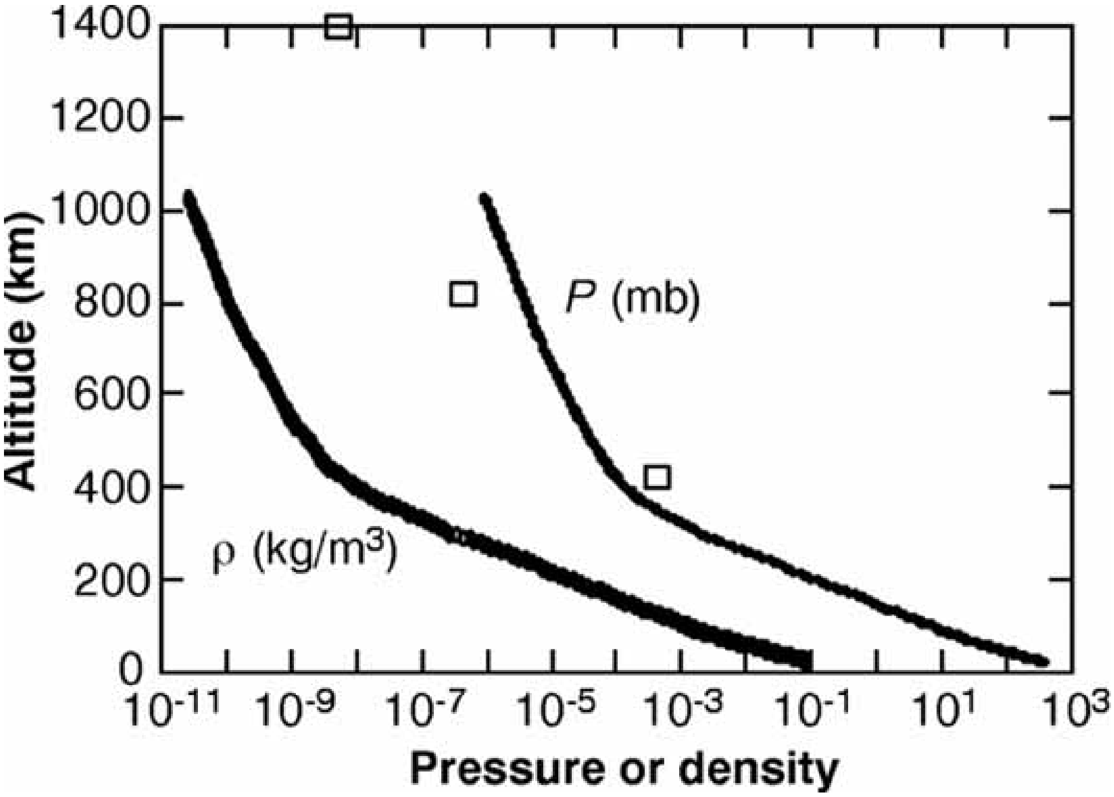


**Figure 1.** Plotted as a function of height above the location in the atmosphere where the atmospheric pressure equals 1 bar, the graph shows the measured atmospheric densities, and the pressures derived from the density data (from reference [25], reprinted with permission from AAAS). The threshold density was 3 x $10^{-11}$ kg/m$^3$; pressures extend from 1 nanobar to 400 mb. These pressures are compared with Voyager occultation results (squares).

Hubbard [24] creates a table using a model of Jupiter's layers which indicates that, at a radius of $6.96\times10^{7}$ m from Jupiter's centre, the pressure is 0.9 GPa (0.009 Mbar, the lowest pressure in the table in question), the temperature is 2000 K, and the density is $5\times10^{-2}$ g cm$^{-3}$ $=50$ kg m$^{-3}$. This could therefore be seen as conditions representing a worst case scenario for near-future technology. Above this layer, the pressures and densities decrease with increasing altitude, although at high altitudes the temperatures are high for a planet so far from the sun (e.g. it is $1100 \pm 200$ K at 1400 km above the altitude where the atmospheric pressure is 1 bar [25]). At the altitude where the atmospheric pressure equals 1 bar, the density is 0.1 kg m$^{-3}$ (Figure 1) and the temperature is around 165 K (Figure 2) [25]. Schematics of Jupiter and Saturn below the radius at which the pressure equals 1 bar are given in Figure 3 [26].

Therefore in the calculation of the effect of fluid loading in Jupiter, two points are chosen: the atmospheric position where the pressure is 1 bar, and the position where the pressure is 0.9 GPa.

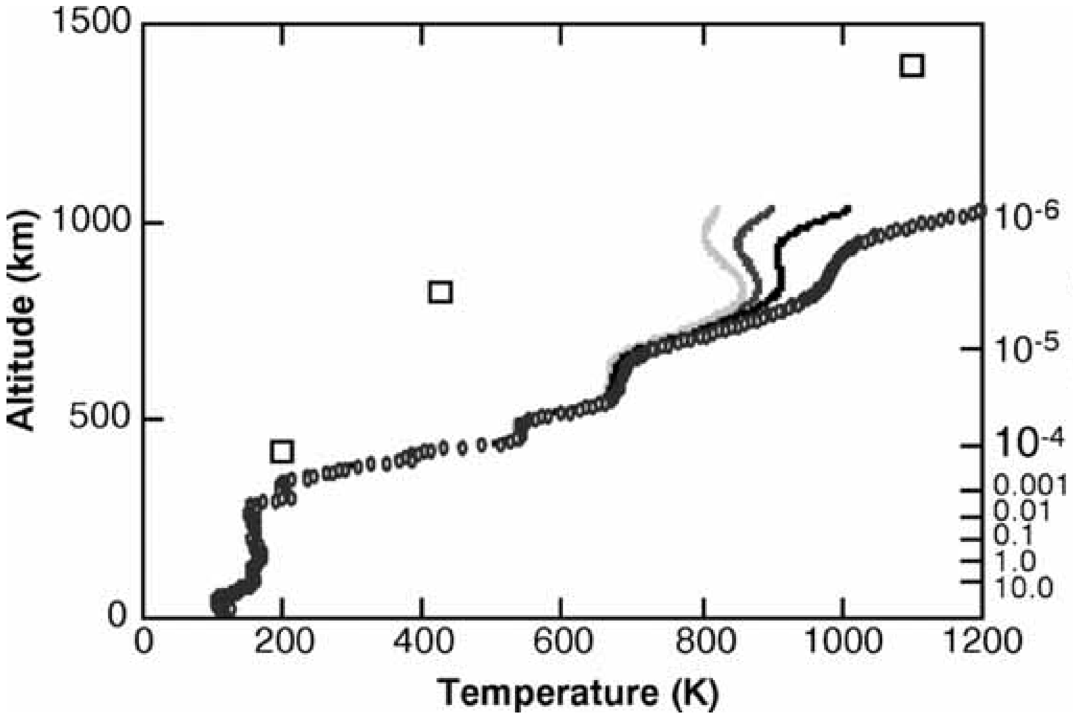


**Figure 2.** Plotted as a function of height above the location in the atmosphere where the atmospheric pressure equals 1 bar, the graph shows the temperatures given by data in Fig. 1 and the equation of state (circles). The four profiles which assume upper boundary temperatures from 800 to 1200 K converge to within ±15 K at 700 km. Voyager solar and stellar occultation results are shown as squares. The exospheric temperature from solar occultation and the point at 400 km altitude agree with the present sounding, but the temperature derived from hydrogen absorption of UV starlight at 800 km differs from the present results by >400 K. This figure is taken from reference [25], reprinted with permission from AAAS.

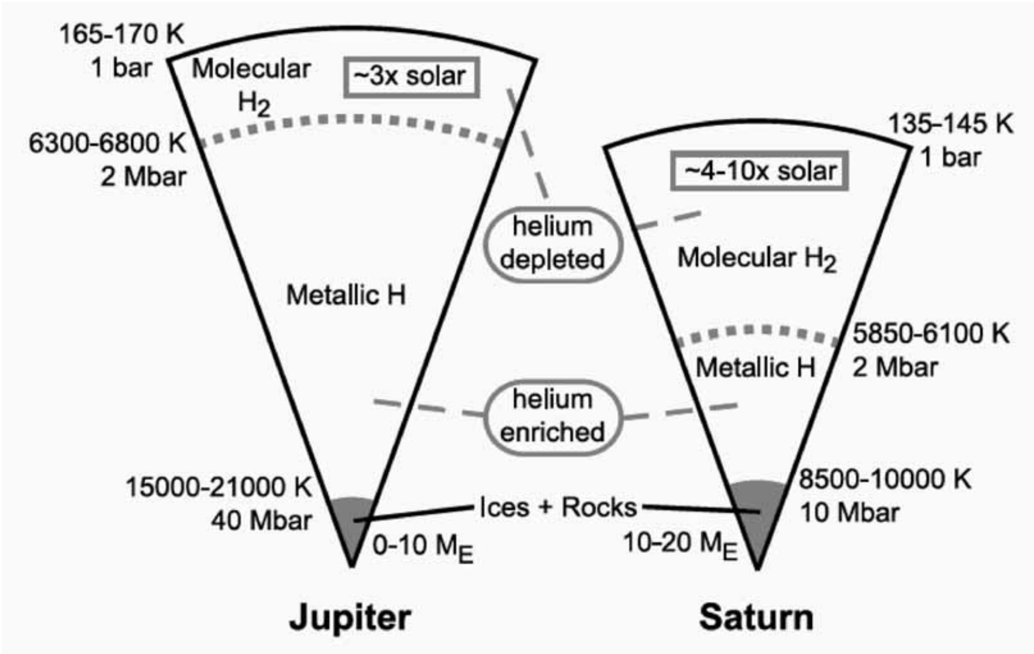


**Figure 3.** Schematic showing the interior structures of Jupiter and Saturn. Pressures and temperature are marked at 1 bar (100 kPa, visible atmosphere), 2 Mbar (200 GPa, near the molecular-to-metallic transition of hydrogen), and at the top of the heavy element core. Temperatures are especially uncertain, and are taken from Guillot [27]. Approximate atmospheric abundances for "metals" (relative to solar) are shown within the grey box, in the molecular H2 region. Possible core masses, in units of $M_E$ (the mass of Earth) are shown as well [28]. Droplets resembling rain of helium and neon precipitate down through the metallic hydrogen layer, depleting the abundance of helium and neon in the upper atmosphere. Reproduced with permission from reference [26].

## 3.2 Candidate sound sources

### (a) Pulsating rigid spheres

Consider a sphere which pulsates at small amplitude in an infinity fluid medium through uniform sinusoidal radial motion of the wall, but that such wall motion does not affect the pressure within the sphere. The radiation impedance of such a source can be found by evaluating the acoustic impedance of spherical waves in the medium at the bubble wall (see Leighton [18§3.2.1(c)(i)]):

$$Z_{\mathrm{r,sphere}} = R_{\mathrm{r,sphere}} + jX_{\mathrm{r,sphere}} = \frac{4\pi a^2 \rho_0 c (ka)^2}{1+(ka)^2} + j\frac{4\pi a^2 \rho_0 c (ka)}{1+(ka)^2}, \tag{14}$$

where $a$ is the equilibrium radius of the sphere, $k = \omega / c$ is the acoustic wavenumber where $c$ and $\rho_0$ are the low-amplitude sound speed and equilibrium density of the fluid. At high frequencies ($ka$>>1) the radiation reactance becomes much less than the radiation resistance for this sphere,

$$R_{\mathrm{r,sphere}} \approx 4\pi a^2 \rho_0 c\,, \qquad (ka >> 1) \qquad \mathbf{(15)}$$

However at low frequencies ($ka$<<1) the components of the radiation impedance tend to the following form:

$$\begin{aligned} R_{\mathrm{r,sphere}} &\approx 4\pi a^2 \rho_0 c (ka)^2; \\ X_{\mathrm{r,sphere}} &\approx 4\pi a^2 \rho_0 c (ka) \Rightarrow m_{\mathrm{r,sphere}} \approx 4\pi a^3 \rho_0 \end{aligned} \quad . \qquad (ka << 1) \qquad \mathbf{(16)}$$

In this limit, the radiation reactance is much greater than the radiation resistance, and the radiation mass equals three times the mass of the fluid displaced [20]).

If such a sphere were to be used as a musical instrument, then a 0.1 m radius instrument emitting in the low audio range (say, O(100 Hz)) would operate in the regime where $ka = a\omega / c = a 2\pi f / c < 1$, but not greatly less than unity.

Therefore the monopole pulsation of a spherical source in the low frequency limit provide the first test case. Equation (16) will be used to assess the magnitude of the radiation mass $m_{\mathrm{r,sphere}} \approx 4\pi a^3 \rho_0$ compared to the inertia of the source *in vacuo* ($m$), and the percentage change in the resonance frequency $f_0$ caused by fluid loading from (12), i.e.:

$$\begin{aligned} \frac{\Delta f}{f_0} \times 100\% &= \left( \sqrt{m / (m + m_{\mathrm{r,sphere}})} - 1 \right) \times 100\% \\ &= \left( \sqrt{m / (m + 4\pi a^3 \rho_0)} - 1 \right) \times 100\% \end{aligned} \quad . \qquad \mathbf{(17)}$$

## (b) Piston in a short open tube with rigid baffled end flange

Consider a short cylindrical tube with rigid walls, of radius *d* and length *l* (*kd*<*kl*<<1), at the base of which is a piston (the motion of which is uniform over the piston's surface). At the open end of the tube is an infinite rigid plane (Figure 4).

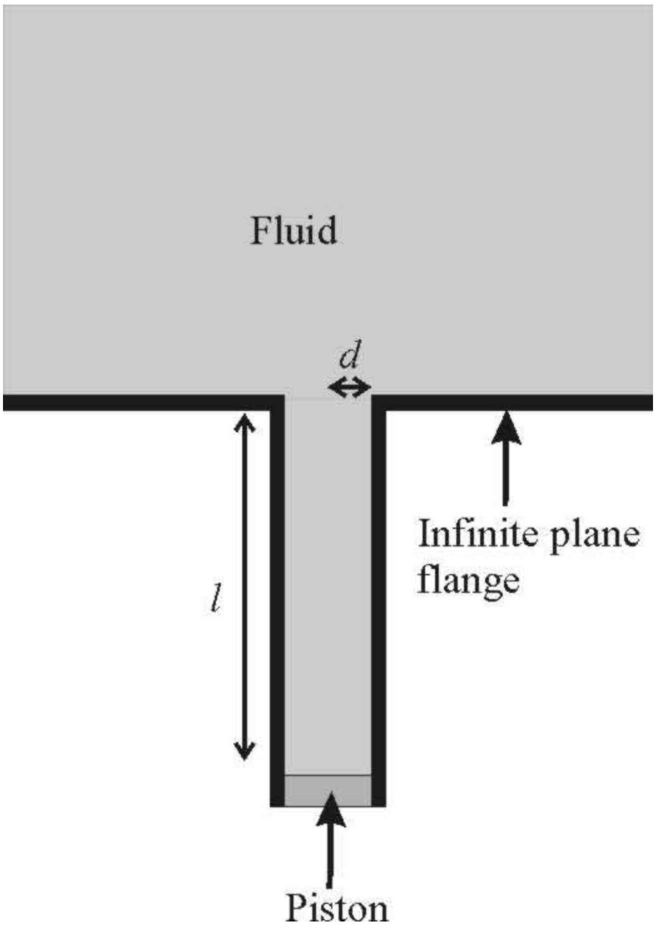


**Figure 4.** Schematic a piston in a short pipe which is open to a semi-infinite fluid by means of an aperture (having the same radius as the pipe (*d*)) that is set in an otherwise infinite rigid flange.

The piston moves harmonically at low frequency (*kd*<*kl*<<1), forcing the fluid above it into motion which contributes an inertial loading (no inertial contribution comes from any fluid below the piston, although it would be a trivial extension to include it). At low frequency the inertia contributed by the fluid in the pipe is equal to the mass of fluid in the pipe ($\rho_0 l\pi d^2$). The inertial contribution from the fluid outside of the pipe can readily be found from the radiation impedance of a baffled piston, as follows. The low frequency radiation resistance, reactance and mass of a baffled piston of radius *d* are [29]:

$$R_{\mathrm{r,piston}} \approx \frac{1}{2}\pi d^2 \rho_0 c(kd)^2;$$
$$X_{\mathrm{r,piston}} \approx \frac{8}{3\pi}\pi d^2 \rho_0 c(kd) \Rightarrow m_{\mathrm{r,piston}} \approx \frac{8}{3\pi}\pi d^3 \rho_0 \quad . \qquad (kd \ll 1) \qquad \textbf{(18)}$$

Therefore the inertial loading caused by the fluid in Figure 4 at low frequencies is [30, 31]:

$$m_{\mathrm{r,pipe}} \approx \rho_0 \pi d^2 l + \frac{8}{3\pi}\rho_0 \pi d^3 \ . \qquad (kd < kl \ll 1) \qquad \textbf{(19)}$$

**(c) Transversely oscillating infinite cylinder**

If an infinite rigid cylinder of radius *b* undergoes transverse oscillation without its cross-section undergoing distortion (the motion is synchronised along the entire length of the cylinder), then at low frequencies ($kb$<<1) the inertial loading caused by the fluid motion that is induced by the cylinder's motion, is of course infinite. The added mass per unit length of cylinder is equal to the mass of fluid displaced by that length of cylinder [31], so that for length *l* of the cylinder the associated added mass is:.

$$m_{\mathrm{r,wire}} \approx \rho_0 \pi b^2 l \ . \qquad (kb \ll 1) \qquad \textbf{(20)}$$

# 4 Results

In this section a range of Tables are presented which indicate the magnitude of the effect of inertial loading for the range of environments discussed earlier, on different sound sources. The percentage change in the frequency (compared to the *in vacuo* frequency $f_0$) is given. These changes are negative since, on its own, inertial loading here decreases the frequency compared to the *in vacuo* emission. The Tables therefore show the frequency of the closest note corresponding to the fluid loaded emission, were the source to emit D oat ground level of Earth. (It is recognized that the physical objects in question may in fact emit different notes if they were constructed, but to allow comparison the $f_0$ of each, when adjusted for the fluid loading of Earth at ground level, is normalized to D at 293.66 Hz). The frequencies of the candidate notes are shown in Tables 1 to 3.

| Pitch of note: | ↓D# | ↓E | ↓F | ↓F# | ↓G | ↓G# | ↓A | ↓A# | ↓B | ↓C | ↓C# | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Frequency (Hz) | 155.56 | 164.81 | 174.61 | 185.00 | 196.00 | 207.65 | 220.00 | 233.08 | 246.94 | 261.63 | 277.18 | 293.66 |

Table 1. Pitch of the notes for the first octave below D 293.66 Hz.

| Pitch of note: | ↓↓↓D# | ↓↓E | ↓↓F | ↓↓F# | ↓↓G | ↓↓G# | ↓↓A | ↓↓A# | ↓↓B | ↓↓C | ↓↓C# | ↓↓D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Frequency (Hz) | 77.78 | 82.41 | 87.31 | 92.50 | 98.00 | 103.83 | 110.00 | 116.54 | 123.47 | 130.81 | 138.59 | 146.83 |

Table 2. Pitch of the notes for the second octave below D 293.66 Hz.

| Pitch of note: | ↓↓↓D# | ↓↓↓E | ↓↓↓F | ↓↓↓F# | ↓↓↓G | ↓↓↓G# | ↓↓↓A | ↓↓↓A# | ↓↓↓B | ↓↓↓C | ↓↓↓C# | ↓↓↓D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Frequency (Hz) | 38.89 | 41.20 | 43.65 | 46.25 | 49.00 | 51.91 | 55.00 | 58.27 | 61.74 | 65.41 | 69.30 | 73.42 |

Table 3. Pitch of the notes for the third octave below D 293.66 Hz.

The subsequent sections generate Tables which indicate the densities of the gases on various worlds, and assesses how these values reflect in the added mass they impart, and how this in turn affects the frequencies generated.

## 4.1 Pulsations of rigid spheres

In this subsection, the fluid loading on two steel spheres, pulsating as rigid sources, is calculated. Since both bodies displace the same amount of fluid, and move it in the same manner, they both incur the same added mass. However the effect that this added mass has on the frequency will be greater for the lighter sphere (see equations (12) and (13)).

For the results of Table 4, it is assumed that the instrument is a hollow sphere of 10 cm outer radius ($a$), having a wall of 1 cm thickness made of steel having a density of 7700 kg/m$^3$. The inertia $m$ associated with the *in vacuo* oscillator is taken to equal the mass of the oscillator $(4\pi\rho_{\mathrm{steel}}/3)(0.1^3-0.09^3)\approx 8.74$ kg.

Table 5 repeats the calculations of Table 4, but now for a sphere with the same outer diameter but a much thinner wall. It is assumed that the instrument is a hollow sphere of 10 cm outer radius ($a$), having a wall of 0.5 mm thickness made of steel having a density of 7700 kg/m$^3$. The inertia $m$ associated with the *in vacuo* oscillator is taken to equal the mass of the oscillator $(4\pi\rho_{\mathrm{steel}}/3)(0.1^3-0.0995^3)\approx 0.48$ kg.

For the same external diameter, the rigid sphere pulsator acquires, for a given location, the same added mass regardless of the wall thickness. However since the change in frequency depends on the ratio of this mass to the *in vacuo* inertia, then the effect of the fluid loading on the frequency depends very much on the value of the *in vacuo* inertia. Hence the effect of fluid loading on the frequency is much greater for the thin-walled sphere than the thick-walled sphere.

Table 4 plots the respective frequency shift which the calculated fluid loading would produce, for a note played at D (293.66 Hz) at ground level on Earth. Assuming for a moment that we are discussing some instrument where the actual generation of the sound is unaffected by the fluid environment other than through fluid loading (not a likely scenario), the fluid loading underwater on Earth would decrease the pitch of the 8.74 kg sphere to 188 Hz (i.e. down to between F# (185.00 Hz) and G (196 Hz)). In contrast, even the large fluid loading at ground level on Venus, or in the Jovian atmosphere when the pressure is 0.9 GPa, is insufficient to reduce the note by a semitone (to the 277.18 Hz which corresponds to C#), although the decrease would cause a perceptible detuning.

| World | Atmospheric Location | Local fluid density ($kg/m^3$) | Low-frequency radiation mass of a pulsating rigid sphere, $m_{\mathrm{r,sphere}} \approx 4\pi a^3 \rho_0$ (kg) | Percentage of $m$ which equals $m_{\mathrm{r,sphere}}$ | $\frac{\Delta f}{f_0} \times 100\%$ | Frequency of the emission that was at D (293.66 Hz) on Earth (Hz) | Closest note (Tables 1 to 3) |
|---|---|---|---|---|---|---|---|
| Earth | At ground level | 1.3 | 0.016 | 0.18 % | -0.093 % | 293.66 | D |
| Mars | At ground level | 0.02 | 0.00025 | 0.0029 % | -0.0014 % | 293.93 | D |
| Venus | At ground level | 65 | 0.82 | 9.3 % | -4.4 % | 281.07 | ↓C# |
| Jupiter | 1 bar level | 0.1 | 0.0013 | 0.014 % | -0.0072 % | 293.91 | D |
| Jupiter | 0.9 GPa level | 50 | 0.63 | 7.2 % | -3.4 % | 283.89 | ↓C# |
| Titan | At ground level | 5.5 | 0.069 | 0.79 % | -0.39 % | 292.77 | D |
| Earth | In infinite body of water at Earth surface conditions | 1000 | 12.58 | 144 % | -36% | 188.18 | ↓F# |

Table 4. Assessment for various scenarios for the effect of fluid loading by selected atmospheres in the Solar System (with the underwater case on Earth shown for comparison) on a rigid pulsating sphere of 10 cm outer radius ($a$), having a wall of 1 cm thickness made of steel. The final column shows the respective frequency shift which the calculated fluid loading would produce, for the component of the sound emission which would be at D (293.66 Hz) at ground level on Earth. To give 293.66 Hz on Earth at ground level, the *in vacuo* frequency would have to be 293.93 Hz.

However the effect of fluid loading is far more noticeable on a thin-walled sphere. Since in Table 5 the note is normalized to 293.66 Hz on Earth, the fact that the fluid loading on Mars is less than that on Earth means that the pitch is slightly increased. The same feature occurs in Jupiter at the 1 bar location. However the dense atmospheres on Titan, Venus and Jupiter at the 0.9 GPa level reduce the pitch very substantially.

| World | Atmospheric Location | Local fluid density (kg/m$^3$) | Low-frequency radiation mass of a pulsating rigid sphere, $m_{\mathrm{r,sphere}} \approx 4\pi a^3 \rho_0$ (kg) | Percentage of $m$ which equals $m_{\mathrm{r,sphere}}$ | $\frac{\Delta f}{f_0} \times 100\%$ | Frequency of the emission that was at D (293.66 Hz) on Earth (Hz) | Closest note (Tables 1 to 3) |
|---|---|---|---|---|---|---|---|
| Earth | At ground level | 1.3 | 0.016 | 3.4 % | -1.7 % | 293.66 | D |
| Mars | At ground level | 0.02 | 0.00025 | 0.052 % | -0.026 % | 298.54 | D |
| Venus | At ground level | 65 | 0.82 | 170 % | -39 % | 181.60 | ↓F# |
| Jupiter | 1 bar level | 0.1 | 0.0013 | 0.26 % | -0.13 % | 298.23 | D |
| Jupiter | 0.9 GPa level | 50 | 0.63 | 131 % | -34 % | 196.44 | ↓G |
| Titan | At ground level | 5.5 | 0.069 | 14 % | -6.5 % | 279.17 | ↓C# |
| Earth | In infinite body of water at Earth surface conditions | 1000 | 12.58 | 2621 % | -81 % | 57.24 | ↓↓↓A# |

Table 5. Assessment for various scenarios for the effect of fluid loading by selected atmospheres in the Solar System (with the underwater case on Earth shown for comparison) on a rigid pulsating sphere of 10 cm outer radius (*a*), having a wall of 0.5 mm thickness made of steel. The final column shows the respective frequency shift which the calculated fluid loading would produce, for the component of the sound emission which would be at D (293.66 Hz) at ground level on Earth. To give 293.66 Hz on Earth at ground level, the *in vacuo* frequency would have to be 298.74 Hz.

## 4.2 The added mass in a model vocal tract

The acoustical features of the vocal tract are not simple, but to assess the added mass imparted by various atmospheres the simple model of section 3.2(b) will be employed (other models could be used, but the results are within the same order). Let the assumed length of the vocal tract be 18 cm, with a diameter of 2 cm ($l$=0.18 m, $d$=0.01 m in the model). For a gas of density $\rho_0$ where $kd < kl$ <<1, the assumed model gives from (19) an added mass of

$$m_{\mathrm{r,pipe}} \approx \rho_0 \left( \pi d^2 l + \frac{8}{3\pi} \pi d^3 \right) \approx \rho_0 (5.65 \times 10^{-5} + 2.67 \times 10^{-6}) \approx 6 \times 10^{-5} \rho_0 \quad \text{kg} \tag{21}$$

with the fluid in the pipe contributing more than twenty times the inertia than the much larger volume of fluid outside of the pipe because within the pipe the fluid motion does not to first order decrease with distance as a result of geometrical spreading [32-36].

Adult human vocal folds have a mass of about 1 gramme each, 15 mm long and vibrate with an amplitude of displacement of about 1 mm [37]. Using these numbers ($m = 2\times10^{-3}$ kg), Table 6 assesses the effect of the various atmospheres on the added mass and frequency for this model.

| World | Atmospheric Location | Local fluid density (kg/m$^3$) | Low-frequency radiation mass of vocal tract $m_{\mathrm{r,pipe}} \approx 6\times10^{-5}\rho_0$ (kg) | Percentage of $m$ which equals $m_{\mathrm{r,pipe}}$ | $\frac{\Delta f}{f_0}\times100\%$ | Frequency of the emission that was at D (293.66 Hz) on Earth (Hz) | Closest note (Tables 1 to 3) |
|---|---|---|---|---|---|---|---|
| Earth | At ground level | 1.3 | 0.000078 | 3.9 | -1.89 | 293.7 | D |
| Mars | At ground level | 0.02 | 1.2E-06 | 0.06 | -0.0299 | 299.2 | D |
| Venus | At ground level | 65 | 0.0039 | 195 | -41.8 | 174.3 | ↓F |
| Jupiter | 1 bar level | 0.1 | 0.000006 | 0.3 | -0.149 | 298.9 | D |
| Jupiter | 0.9 GPa level | 50 | 0.003 | 150 | -36.8 | 189.3 | ↓F# |
| Titan | At ground level | 5.5 | 0.00033 | 16.5 | -7.35 | 277.3 | ↓C# |
| Earth | In infinite body of water at Earth surface conditions | 1000 | 0.06 | 3000 | -82.04 | 53.8 | ↓↓↓G# |

Table 6. Assessment for various scenarios for the effect of fluid loading by selected atmospheres in the Solar System (with the underwater case on Earth shown for comparison) on an adult vocal tract using the model outlined in section 4.2. The final column shows the respective frequency shift which the calculated fluid loading would produce, for the component of the sound emission which would be at D (293.66 Hz) at ground level on Earth. To give 293.66 Hz on Earth at ground level, the *in vacuo* frequency would have to be 299.33 Hz.

Assuming that a human child has a vocal tract which is 10 cm long and vocal folds of total mass vocal folds ($m = 5\times10^{-4}$ kg), the effect of the various atmospheres on the added mass and frequency for this model are shown in Table 7. Assuming that the child's vocal tract has a diameter of 1.5 cm ($l$=0.1 m, $d$=$7.5\times10^{-3}$ m in the model). For a gas of density $\rho_0$ where $kd < kl$ <<1, the assumed model gives from (19) an added mass of

$$m_{\mathrm{r,pipe}} \approx \rho_0\left(\pi d^2 l + \frac{8}{3\pi}\pi d^3\right) \approx \rho_0(1.77\times10^{-5} + 1.1\times10^{-6}) \approx 2\times10^{-5}\rho_0 \quad \text{kg} \qquad \textbf{(22)}$$

| World | Atmospheric Location | Local fluid density ($kg/m^3$) | Low-frequency radiation mass of vocal tract $m_{\text{r,pipe}} \approx 2\times10^{-5}\rho_0$ (kg) | Percentage of $m$ which equals $m_{\text{r,pipe}}$ | $\frac{\Delta f}{f_0}\times100\%$ | Frequency of the emission that was at D (293.66 Hz) on Earth (Hz) | Closest note (Tables 1 to 3) |
|---|---|---|---|---|---|---|---|
| Earth | At ground level | 1.3 | 0.000026 | 5.2 | -2.50 | 293.66 | D |
| Mars | At ground level | 0.02 | 4E-07 | 0.08 | -0.039 | 301.08 | D |
| Venus | At ground level | 65 | 0.0013 | 260 | -47 | 158.75 | ↓D# |
| Jupiter | 1 bar level | 0.1 | 0.000002 | 0.4 | -0.20 | 300.60 | D |
| Jupiter | 0.9 GPa level | 50 | 0.001 | 200 | -42 | 173.90 | ↓F |
| Titan | At ground level | 5.5 | 0.00011 | 22 | -9.5 | 272.69 | ↓C# |
| Earth | In infinite body of water at Earth surface conditions | 1000 | 0.02 | 4000 | -84 | 47.04 | ↓↓↓F# |

Table 7. Assessment for various scenarios for the effect of fluid loading by selected atmospheres in the Solar System (with the underwater case on Earth shown for comparison) on a child's vocal tract using the model outlined in section 4.2. The final column shows the respective frequency shift which the calculated fluid loading would produce, for the component of the sound emission which would be at D (293.66 Hz) at ground level on Earth. To give 293.66 Hz on Earth at ground level, the *in vacuo* frequency would have to be 301.2 Hz.

For these parameter values the pitch shift due to added mass is slightly greater in the child than the adult, although these values can be taken as indicative only.

## 4.3 The added mass in vibrating wire

The oscillating components of most string instruments go far beyond the wire or string itself, to include other solid parts (bridge, body etc) which in turn generate fluid motions and incur an added mass component. For this simple calculation, the added mass associated with the wire alone will be considered. Strings masses vary, and so the calculations are done for a 'light string' ($10^{-4}$ kg per metre, 0.25 mm radius) and a 'heavy string' ($10^{-2}$ kg per metre, 1 mm radius), using the model of Section 3.2(c). From equation (20), $m_{\text{r,wire}} \approx \rho_0 \pi b^2 l$, the added masses and effects on the frequency are shown for the light wire in Table 8 ($m_{\text{r,wire}} \approx \rho_0 1.96\times10^{-7}$ kg m$^{-1}$), and for the heavy wire in Table 9 ($m_{\text{r,wire}} \approx \rho_0 3.14\times10^{-6}$ kg m$^{-1}$).

| World | Atmospheric Location | Local fluid density (kg/m$^3$) | Low-frequency radiation mass per unit length of light wire $m_{\mathrm{r,wire}} \approx \rho_0 \pi b^2 l$ (kg) | For a given length of wire, %age of solid $m$ which equals radiation mass (%) | $\frac{\Delta f}{f_0} \times 100\%$ | Frequency of the emission that was at D (293.66 Hz) on Earth (Hz) | Closest note (Tables 1 to 3) |
|---|---|---|---|---|---|---|---|
| Earth | At ground level | 1.3 | 2.548E-07 | 0.2548 | -0.12716 | 293.66 | D |
| Mars | At ground level | 0.02 | 3.92E-09 | 0.00392 | -0.00196 | 294.02 | D |
| Venus | At ground level | 65 | 1.274E-05 | 12.74 | -5.8195 | 276.92 | ↓C# |
| Jupiter | 1 bar level | 0.1 | 1.96E-08 | 0.0196 | -0.0098 | 294.00 | D |
| Jupiter | 0.9 GPa level | 50 | 0.0000098 | 9.8 | -4.56694 | 280.60 | ↓C# |
| Titan | At ground level | 5.5 | 1.078E-06 | 1.078 | -0.53468 | 292.46 | D |
| Earth | In infinite body of water at Earth surface conditions | 1000 | 0.000196 | 196 | -41.8762 | 170.90 | ↓F |

Table 8. Assessment for various scenarios for the effect of fluid loading by selected atmospheres in the Solar System (with the underwater case on Earth shown for comparison) on a light guitar string using the model outlined in section 4.3. The final column shows the respective frequency shift which the calculated fluid loading would produce, for the component of the sound emission which would be at D (293.66 Hz) at ground level on Earth. To give 293.66 Hz on Earth at ground level, the *in vacuo* frequency would have to be 294.03 Hz.

| World | Atmospheric Location | Local fluid density (kg/m$^3$) | Low-frequency radiation mass per unit length of light wire $m_{\mathrm{r,wire}} \approx \rho_0 \pi b^2 l$ (kg) | For a given length of wire, %age of solid $m$ which equals radiation mass (%) | $\frac{\Delta f}{f_0} \times 100\%$ | Frequency of the emission that was at D (293.66 Hz) on Earth (Hz) | Closest note (Tables 1 to 3) |
|---|---|---|---|---|---|---|---|
| Earth | At ground level | 1.3 | 0.000004082 | 0.04082 | -0.0204 | 293.6601 | D |
| Mars | At ground level | 0.02 | 6.28E-08 | 0.000628 | -0.00031 | 293.7191 | D |
| Venus | At ground level | 65 | 0.0002041 | 2.041 | -1.00514 | 290.7677 | D |
| Jupiter | 1 bar level | 0.1 | 0.000000314 | 0.00314 | -0.00157 | 293.7154 | D |
| Jupiter | 0.9 GPa level | 50 | 0.000157 | 1.57 | -0.77588 | 291.4411 | D |
| Titan | At ground level | 5.5 | 0.00001727 | 0.1727 | -0.08624 | 293.4667 | D |
| Earth | In infinite body of water at Earth surface conditions | 1000 | 0.00314 | 31.4 | -12.7627 | 256.2335 | ↓C |

Table 9. Assessment for various scenarios for the effect of fluid loading by selected atmospheres in the Solar System (with the underwater case on Earth shown for comparison) on a heavy guitar string using the model outlined in section 4.3. The final column shows the respective frequency shift which the calculated fluid loading would produce, for the component of the sound emission which would be at D (293.66 Hz) at ground level on Earth. To give 293.66 Hz on Earth at ground level, the *in vacuo* frequency would have to be 293.72 Hz.

Not unsurprisingly, the light guitar string used here is more affected by the fluid loading than the heavy string, since the effect is based on the ratio of the mass of the fluid displaced to the body-averaged mass of the displacing object.

# 5 Conclusions

This report considers the effect of the added mass that results from fluid loading on the frequency of a sound source. Simple calculations are undertaken using the examples of pulsating rigid spheres, a piston in pipe, and vibrating wires.

It was shown that, given the range of locations where a surviving man-made probe might generate sound in the Solar System, the effect of the added mass depends not only on the density of the fluid surrounding the source, but also depends on the details of the source itself (particularly its *in vacuo* inertia: the lighter this is, the greater the effect of the added mass upon the vibration frequency for the same displaced volume of fluid). Two objects of the same external boundary (material and size) that move in the same way, will incur the same added mass, but the effect on the frequency will be greater for the lighter body (as illustrated by the spheres in Section 4.1). In practical terms, this means that a metal string on an instrument might experience negligible frequency shift, but a plastic string of the same size (were it to survive) could experience an observable frequency shift (neglecting the thermal issues of survivability and expansion-related tension changes). The examples chosen illustrate that the calculations must be undertaken for each sound source: the pitch of an organ pipe of a given size is determined primarily through the local sound speed, whilst the pitch of the voice is independent of the sound speed but can be affected by the added mass (Section 4.2).

Whilst the massive examples (the heavy pulsating sphere of Table 4 and the heavy wire of Table 8) were only a little detuned even by the dense atmospheres of Venus, Titan and Jupiter at the 0.9 MPa level, the less massive examples (the light sphere of Table 5 and the vocal cords of Table 6) sustained more significant pitch shifts (of around half an octave on Venus and at the 0.9 MPa level on Jupiter, and a more modest semitone shift on Titan). Fluid loading is less on Mars than on Earth, so that the reduction in pitch from the *in vacuo* frequency is less, and if fluid effect has the dominant effect for a particular sound source on Mars, it would be to make the note sharp compared to Earth tuning. These comments apply of course only the effect of inertial fluid loading, taken in isolation of other effects (such as dissipation, thermal expansion etc.).

These simple calculations are for illustrative purposes only and assess the effects of fluid loading in isolation to other factors. This report has restricted itself to consideration of the added mass, from the radiation reactance $X_r$. However alien atmospheres can affect the characteristic frequencies of physical oscillators (such as musical instruments) through other means. A significant radiation resistance $R_r$ will affect the dissipation, decreasing a resonance frequency and the associated quality factor. Sound speed changes affect instruments in different ways, and the atmospheric conditions can strongly influence the generation of the sounds themselves. The added mass effect discussed in this report is a single factor in the complex mix which determines the eventual sound produced.

The results suggest that, even though some of the atmospheres in the Solar system are considerably more dense than those found on Earth, nevertheless the fluid loading for structures in survivable conditions is significantly less than that found when the sound source is placed underwater on Earth. This is important for testing purposes since the importance of fluid loading to some structures may not be in the added mass for acoustical purposes, but in the inertial and dissipative effect which affect their dynamical performance (e.g. with respect to the ability of the structure to survive dynamic conditions). Just as one would not design an oil rig without taking into account the fluid/structure interactions involving the ocean, so too should the dynamics of probes require account to be taken of the dense atmospheres they might encounter. Survivability, structural resonance and damping, and the generation of turbulence around probes all rely on the fluid/structure interactions which are not simply to replicate on Earth in, for example, drop tests through Earth's atmosphere.

Whilst the fluid loading on other simple geometries can be calculated [38], the issue of fluid/structure interaction provides a wealth of complex scenarios only some of which are amenable to realistic simplification [39-41], and even if one considers musical instruments alone, the variety structures that interact with the fluid and generate fluid loading provide a significant level of complexity. The role of fluid coupling on Earth is still under research in the dynamics of percussion, wind [42] and string [43] instruments. The pulsating rigid sphere portrayed here is useful for calculations in that it constrains into spherically-symmetric motion fluid significant contributions to the added mass. However very many instruments cannot modelled as such pulsators. Simplified models were deployed for the vocal tract and for 'light' and 'heavy' guitar strings, though the models do not capture the complexity of the real sound sources. However the general principle elucidated from these examples is that the greater the difference between the mass of fluid displaced and the body-averaged mass of the object which does the displacing, the less is the effect of the added mass on the frequency. Therefore if one constructed two percussion instruments which vibrated in the same way except that in the one the vibrating solid was a light membrane but in the other was metallic (imaging a cross between tympani and steel drums), then fluid loading would affect the membrane more than the steel (dropping the pitch on worlds where the atmosphere was more dense than it is on Earth, and increasing the note on worlds where it is less dense, such as Mars). Within the Solar System, noticeable reduction in frequency is found in the thick atmospheres of Venus, Titan and at depth in the gas giants for certain sound sources, although the effect is very dependent on the geometry and the mass of the vibrating solid: even on a single stringed instrument, it is possible for one string to be noticeably affected by fluid loading and the other string to be affected hardly at all.

The effects of extra-terrestrial environments on acoustical generation and propagation go far beyond the issue of fluid loading, which is seen to be a relatively small effect for the worlds studied here. Other atmospheres and oceans and worlds in our solar system, and beyond it (150 giant worlds have to date been discovered orbiting solar-like stars [27]) will provide a range of environments in which, years before our probes reach them, have since their formation been perturbed by acoustic phenomenon that offer us opportunities for research. From the volcanoes of Io to the 'dust devils' of Mars, from the waters of Enceladus and Europa to the lakes of Titan, from the impacts of comets and asteroids sending shock waves through distant worlds to density fluctuations propagating in the solar wind, the Solar System is a dynamic environment which can reveal much through acoustics. We have already sent acoustical instrumentation on missions to the atmospheres of Venus and Titan, and Mars, and may one day explore the gas giants by dirigible. Astroacousticians will have an important role in providing the modelling and experimentation (in model extraterrestrial environments) required to plan the missions and design the instrumentation.

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