A SEISMIC INVESTIGATION OF THE INTERIOR OF A COMET
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Seismology can be a powerful method for investigating the inner structure and dynamic processes of a comet. Whereas remote sensing and in situ experiments (with the exception of electromagnetic sounding) can only sample the outermost skin of a comet, seismic waves can potentially probe the entire volume of the body in detail. We have proposed an experiment, which has been provisionally selected, to detect and analyze the seismic activity of a comet/P/Tempel 1 using the RoLand Surface Science Package of the Rosetta Mission. This novel extension of seismology to comets will provide a unique opportunity to study the dynamic activity and probe the deep internal structure of a member of this fascinating and poorly known class of objects.

The interior structure of comets is key to understanding numerous cometary phenomena. For example, such basic physical processes in comets as heat transport, gas diffusion, and the overall strength of the body are strongly coupled with material properties such as density, porosity, and elastic constants. The large-scale structure of cometary nuclei may reflect the origin of comets in the primordial nebula (e.g., the presence of discrete “cometesimals” within the interior). Structural boundaries beneath the surface may shed light on consequences of the thermal evolution of the nucleus, such as the cementation of primordial material, the buildup of sublimation crusts, or even on the bulk differentiation of the comet. Structural properties of comets are nearly completely unknown. Estimates of the density of comets vary from 0.2 to 2 Mg/m³, and the strength from 100 Pa to 10 MPa. Whereas orbital measurements will obtain the mass and volume of the comet (yielding its bulk density), only a sounding experiment can obtain the internal distribution of actual density, which bears directly on the porosity and the ice/silicate ratio. Similarly, measurement of seismic wave velocity will yield the elastic parameters of the cometary material, resulting in a direct determination of the strength.

Cometary seismology is an immature field. Perhaps the greatest uncertainty is in the frequency with which events capable of producing detectable signals will occur. Whereas there are no direct measurements from which to base an estimate, there are several reasons to believe that a sufficient number of events will occur during the surface lifetime of the RoLand SSP to make this experiment viable. First, a short-period comet such as P/Tempel 1 is in a constant state of thermal disequilibrium. This will result in stresses in the outer layers that should cause cracking. Second, the activity of a comet (such as jetting, or outbursts) becomes increasingly intense as it approaches perihelion. These events, as observed on Halley by Giotto and inferred from orbital perturbations of other comets, appear to have more than enough energy to be detectable by a sensitive seismometer on the surface. As this type of activity will occur preferentially on the day side of the comet and will migrate with the comet’s rotation, a relatively complete “tomographic” coverage of the interior could result. And third, we calculate that a meteorite of mass less than a gram, impacting anywhere on the comet at typical impact velocity, should be detectable by our instrument. Even much smaller micrometeorites, hitting in the vicinity of the lander, will produce useful signals. Thus we are confident that we will have an adequate number of signals to analyze for information about the interior.

Seismic sources, whether they be induced by internal stress or produced by external impacts, create vibrations of the medium which propagate as elastic waves. These waves come in three basic varieties: body waves, surface waves, and normal modes, or free oscillations. Each of these wave types has a characteristic way in which it “samples” the medium, and each requires a different type of analysis. Body waves are the simple propagation of elastic vibrations through the body. Their velocity depends directly on the elastic moduli and the density along their path, and they can be reflected and refracted by changes in those velocities. In this experiment, we do not have the luxury of multiple stations, so we will attempt to use multiple interior reflections to provide relatively well-determined paths along which to compute velocities. The three-component measurement of the first motion of the initial arrival will help determine the direction of propagation. As the source of the signal is very nearly an impulse, the extended length of the wavetrain in a highly scattering medium is due primarily to arrivals that have taken progressively longer paths. Thus the length of the coda gives a measure of the attenuation of the medium, which in turn is related to the porosity and temperature. Surface waves propagate only along the surface of the body, and their displacement field dies off exponentially with depth. Therefore they will provide information about the outermost layers of the comet (perhaps several tens of meters). Their
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Interpretation is aided by the fact that they are dispersive, with the higher frequency components (which sample shallowest layers) traveling more slowly than the low frequency components (which sample deeper). Thus one can derive the velocity profile near the surface from a single surface wave train. Normal modes are the whole-body oscillations of the comet. These oscillations are a function of its density and elastic structure, and are expected to have periods ranging up to a few seconds (compared to thousands of seconds for the Earth). The measurement of the normal mode spectrum of the low-frequency portion of a large seismic event can in principle yield the gross average structure. This analysis is complicated by the non-sphericity of the comet, but knowledge of the shape derived from Rosetta imaging and vector measurement of the acceleration field of the oscillation (allowing the separation of degenerate modes) should help considerably with this difficult modeling problem.

It is clear that seismic signals in a comet will be extremely small. For example, in a variety of situations the strength of the seismic source will scale roughly with the gravitational force of the body. Thus, given that the surface gravity of P/Wirtanen is expected to be of order $10^{-3}$ that of the Earth, we must use the most sensitive seismometer possible in order to detect the comet's activity. However, a seismometer on a comet also has the advantage of measuring the seismic signal against the low offset of the comet's gravitational field: the instrument is essentially a microgravity accelerometer with no (to first order) additional symmetry imposed by a constant gravitational field. Both mechanical design and thermal design are hence greatly facilitated.

Our seismometer will consist of four identical single-axis sensors arranged in a tetrahedral pyramid (see figure 1). Such a configuration reflects the high symmetry of the steady-state field while providing for over-determination of the three components of any seismic signal. Such over-determination allows self-calibration of each axis of the sensor after deployment through consistency checking. Each sensor will consist of a silicon micromachined mechanical structure with transducer/feedback electronics attached on printed circuit boards in an open sandwich structure. The mechanical structure will consist of three silicon micromachined wafers fusion bonded to produce a single sandwich. The two outer layers will contain the fixed plates and will be identically manufactured. The center plate will contain the proof mass and associated plates suspended by a series of silicon dioxide (quartz) springs. The UHFC (ultra-high frequency capacitive) transducer and feedback circuits for each axis will be implemented on separate printed circuit boards, each of which will be mounted onto its respective sensor. The UHFC circuit contains two arms, the outputs being summed to produce a single differential capacitance signal. The resulting signal is used as the control for a force-feedback circuit which electrostatically levitates the proof mass to keep it centered between the fixed capacitor plates. The feedback voltage is then the output of each axis of the seismometer. The four sensors will be mounted on a frame, which is in turn attached to the deployment assembly of the seismometer. The completed sensor unit will be packaged to ensure that spurious signals (notably mechanical vibrations from the lander and temperature drift of the suspension) are suitably attenuated. It should be noted that due to the microgravity environment, the temperature coefficient of the sensors will already be reduced by a factor of at least $10^4$ compared to terrestrial seismometers. Hence thermal control, normally a major concern in seismometry, can be passive, lightweight and of simple design.

Prototype testing indicates that a noise floor of $10^{-9}$ m/sec$^2$/Hz (limited primarily by the Brownian noise of the low-mass transducer) should be achievable over a frequency range of 0.05 to 100 Hz. This should provide sufficient sensitivity to support the first seismic investigation the interior structure and processes of a comet.

Figure 1. Four-component (three-axis) seismic sensor assembly (actual size). Cutaway shows the sandwich structure of the mechanical sensor. All transducer and feedback electronics are contained on the interior surface of the tetrahedral volume.