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Europa's small impactor flux and seismic detection predictions

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ABSTRACT

Europa is an attractive target for future lander missions due to its dynamic surface and potentially habitable sub-surface environment. Seismology has the potential to provide powerful new constraints on the internal structure using natural sources such as faults or meteorite impacts. Here we predict how many meteorite impacts are likely to be detected using a single seismic station on Europa to inform future mission planning efforts. To this end, we derive: (1) the current small impactor flux on Europa from Jupiter impact rate observations and models; (2) a crater diameter *versus* impactor energy scaling relation for icy moons by merging previous experiments and simulations; and (3) scaling relations for seismic signal amplitudes as a function of distance from the impact site for a given crater size, based on analogue explosive data obtained on Earth's ice sheets. Finally, seismic amplitudes are compared to predicted noise levels and seismometer performance to determine detection rates. We predict detection of 0.002–20 small local impacts per year based on P-waves travelling directly through the ice crust. Larger regional and global-scale impact events, detected through mantle-refracted waves, are predicted to be extremely rare (10^{-8}–1 detections per year), so are unlikely to be detected by a short duration mission. Estimated ranges include uncertainties from internal seismic attenuation, impactor flux, and seismic amplitude scaling. Internal attenuation is the most significant unknown and produces extreme uncertainties in the mantle-refracted P-wave amplitudes. Our nominal best-guess attenuation model predicts 0.002–5 local direct P detections and 6×10^{-6}–0.2 mantle-refracted detections per year. Given that a plausible Europa landed mission will only last around 30 days, we conclude that impacts should not be relied upon for a seismic exploration of Europa. For future seismic exploration, faulting due to stresses in the rigid outer ice shell is likely to be a much more viable mechanism for probing Europa's interior.

1. Introduction

Europa, the second of Jupiter's Galilean satellites, has long been considered an attractive target for lander missions due to its active surface processes and potentially habitable interior (Pappalardo et al., 2013). So far, Europa has been investigated using remote sensing by Voyagers 1 and 2 (1979, flyby missions passing through the jovian system), Cassini-Huygens (2000, *en route* to Saturn), New Horizons (2006, *en route* to Pluto), and the Galileo Jupiter orbiter (1995–2003). Results from these missions are reviewed in detail by Pappalardo et al. (2009). Following these spacecraft observations the existence of liquid water beneath an icy outer shell has been proposed (e.g., Cassen et al., 1979; Carr et al., 1998; Kivelson et al., 2000). The sub-surface ocean is predicted to be in direct contact with a rocky mantle, giving rise to conditions analogous to those on Earth's seafloor (Gowen et al., 2011). The possibility of chemical interaction across the rock-water boundary has led to active discussion of a habitable sub-surface environment (e.g., Reynolds et al., 1983; McCollom, 1999; Chyba, 2000; Chyba and Phillips, 2001, 2002).

Although previous missions have taught us much about Europa and the jovian system, many exciting questions remain unanswered (Squyres, 2011), particularly regarding surface activity and internal structure. Recently, the Jupiter Icy Moon Explorer (JUICE) orbiter mission was selected for the L1 launch slot of ESA's Cosmic Vision science programme to explore Jupiter and its potentially habitable icy moons including Europa (Grasset et al., 2013). Future missions could include a lander and one of the aims of NASA's recently announced Europa Clipper mission is to perform reconnaissance for future landing sites (Pappalardo et al., 2015). Some of the most recent mission configurations even include a lander element, with the potential to deliver instruments to the surface.

One of the best ways to probe icy moon interiors in any future mission will be with a surface-based seismic investigation.

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The Apollo seismic experiment, installed by astronauts, enhanced our knowledge of the lunar interior dramatically, including: lunar density (Bills and Ferrari, 1977), velocity structure (Goins et al., 1981; Lognonne et al., 2003; Nakamura, 1983), and seismic attenuation (Goins et al., 1981; Nakamura, 1976; Nakamura and Koyama, 1982). On Mars, the Viking seismometer was intended to measure martian seismicity, but its position on the lander deck meant it was unable to capture any definitive seismic events due to poor coupling with the ground and sensitivity to wind noise (Anderson et al., 1976). NASA's 2018 InSight Mars lander aims to obtain more representative seismic data and will use a robot arm to deploy dual seismometers directly onto Mars' surface protected by a wind and thermal shield (Banerdt et al., 2013). On Europa, future missions may be able to deploy compact seismometers (e.g. Pike et al., 2010) to the surface in a cost effective way using penetrator technology (Collinson and UK Penetrator Consortium, 2008; Gowen et al., 2011).

Europa has a relatively small number of impact craters (Zahnle et al., 2003), which suggests a young and geologically active surface (Pappalardo et al., 2009). This makes it a promising target for seismic investigation as natural sources could be used to probe the internal structure (Lee et al., 2003; Panning et al., 2006). To aid future mission design it is important to predict in advance which kind of sources will produce the most detectable seismic signals. Two of the most promising seismic source candidates are: (1) fracturing or cracking of the ice crust driven by tidal forces; and (2) surface impacts by small comet- or asteroid-derived meteorites.

Fracturing of Europa's ice crust driven by tidally induced stresses is expected to be the main source of seismicity (Lee et al., 2003; Panning et al., 2006) and has been the main focus of research to date. The types and likely seismic magnitudes of such faulting are reviewed in detail by Panning et al. (2006) and include tensile cracks, normal faults, and strike-slip faults. The most common fracturing events are expected to be tensile cracking of the rigid outer ice shell driven by diurnal stresses induced by Europa's eccentric orbit around Jupiter. Estimates of diurnal stress range from 40–100 kPa (Hoppa et al., 1999; Leith and McKinnon, 1996) and should result in many small seismic events during each orbit, with crack depths of a few hundred metres and moment magnitudes of $M_W \sim 2$ (Lee et al., 2003; Panning et al., 2006). Note that moment magnitude M_W is commonly used to describe the size of an earthquake or planet-quake and is defined from the seismic moment M released in Nm according to $M_W = 2/3(\log_{10} M - 9.1)$ (Kanamori, 1977). Larger stresses of ∼3–10 MPa can build up over longer time periods due to various mechanisms including Europa's asynchronous orbit, obliquity, polar wander, or ice shell freezing (McEwen, 1986; Rhoden et al., 2011; Wahr et al., 2009). These could result in much larger faulting events, such as the normal faults observed by Nimmo and Schenk (2006) that were estimated to require a driving stress of around 6–8 MPa and produce Europa-quakes with moment magnitudes of $M_W \sim 5$–6. Large strike-slip faults (McEwen, 1986) could result in similar sized events (Panning et al., 2006).

Large normal or strike-slip faults with $M_W \sim 5$ should be detectable globally at long-period with a reasonably high performance surface seismometer deployment, whereas much smaller events from diurnal tensile cracking would only be detectable locally (Panning et al., 2006). However, the exact occurrence rate of such seismic events includes extreme uncertainties as it depends on fracture/crack depth, crustal thickness, and the crust's depth-temperature profile, which are difficult to determine from current data. In addition, under the most plausible mission scenarios, which include only a single seismometer, it will be challenging to obtain the location and source mechanism details of a complex fault source. This will increase the uncertainty in any determinations of internal structure.

In contrast, meteorite impacts generate seismic energy during crater formation with a relatively simple isotropic source function (Teanby and Wookey, 2011), and could potentially be located using other methods such as surface imaging from an orbiting spacecraft (Daubar et al., 2013; Malin et al., 2006). The frequency of meteorite sources are also somewhat more predictable than that of fault sources and can be constrained by recent observations of impacts into Jupiter (Hueso et al., 2013) and crater populations on the Galilean satellites (Zahnle et al., 1998; Zahnle et al., 2003). In addition, future missions such as JUICE will improve our understanding of the small impactor population with high resolution imaging of Europa and Ganymede of up to 6 m/pixel (Grasset et al., 2013). Small locally detectable impacts would allow determination of the ice crust structure, whereas larger impacts could release enough energy to be detectable at teleseismic (global-scale) distances, which would be well suited to determining deep internal structure.

In this paper, we estimate how many impacts could be detected using a single surface-deployed seismometer, and determine whether impacts could provide a reliable additional source for a future seismic investigation of Europa.

2. Impacts on Europa

2.1. Current impactor flux

According to high-resolution images from the Galileo spacecraft, small impact craters are abundant on Europa (Bierhaus et al., 2001). However, the rate of small impacts that produce craters with diameters less than 1 km is poorly constrained by direct surface observations as a large number of small craters on Europa are "secondaries"; i.e. craters formed by material ejected from large primary impact craters (Bierhaus et al., 2005; Zahnle et al., 2008). Fortunately, the current small impactor flux into Jupiter is relatively well constrained by observations of impact flashes (Hueso et al., 2013). Therefore, to avoid the issues of secondary craters, our approach is to use Jupiter's impact flux observations, combined with the relative impact probability on Europa compared to Jupiter, to determine Europa's current impact rate.

Hueso et al. (2013) report the impact rate of small objects into Jupiter's atmosphere based on regular amateur astronomer observations of impact flashes, which provide a direct estimate of impact energy. In total three flashes were observed at times close to Jupiter's opposition, when many amateurs were able to observe the planet: one on June 3, 2010, one on August 20, 2010, and one on September 10, 2012. Hueso et al. (2013) used the measured light curves to estimate impactor energies and determine equivalent impactor diameters in the 5–20 m range by assuming a typical impact velocity of 60 km s^{-1} and densities in the range 250–2000 kg m^{-3}. Hueso et al. (2013) then compare the impactor diameters with impactor diameter distributions estimated from crater counts (Schenk et al., 2004; Zahnle et al., 2003) and dynamical modelling (Levison et al., 2000). Based on estimates of the effective observation time coverage, Hueso et al. (2013) propose that around 12–60 objects with diameters of 5–20 m impact Jupiter each year and conclude that the impact rate of ecliptic comets estimated by Levison et al. (2000) is the most consistent with their observations.

In the jovian system, ecliptic comets (e.g. Jupiter-family comets) are generally regarded as the dominant source of primary craters (Burger et al., 2010; Zahnle et al., 1998; Zahnle et al., 2003). Asteroids from the main belt, Trojan, or Hilda groups provide a potential secondary impactor population. For example, Sánchez-Lavega, Wesley, Orton, et al., (2010) used orbital analysis to determine that the 2009 Jupiter impact event had a roughly equal probability of being an asteroid or comet. Subsequent near infrared observations of the impact site by Orton et al. (2011) indicated silicate spectral