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Linking Europa's plume activity to tides, tectonics, and liquid water

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ABSTRACT

Much of the geologic activity preserved on Europa's icy surface has been attributed to tidal deformation, mainly due to Europa's eccentric orbit. Although the surface is geologically young (30–80 Myr), there is little information as to whether tidally-driven surface processes are ongoing. However, a recent detection of water vapor near Europa's south pole suggests that it may be geologically active. Initial observations indicated that Europa's plume eruptions are time-variable and may be linked to its tidal cycle. Saturn's moon, Enceladus, which shares many similar traits with Europa, displays tidally-modulated plume eruptions, which bolstered this interpretation. However, additional observations of Europa at the same time in its orbit failed to yield a plume detection, casting doubt on the tidal control hypothesis. The purpose of this study is to analyze the timing of plume eruptions within the context of Europa's tidal cycle to determine whether such a link exists and examine the inferred similarities and differences between plume activity on Europa and Enceladus. To do this, we determine the locations and orientations of hypothetical tidally-driven fractures that best match the temporal variability of the plumes observed at Europa. Specifically, we identify model faults that are in tension at the time in Europa's orbit when a plume was detected and in compression at times when the plume was not detected. We find that tidal stress driven solely by eccentricity is incompatible with the observations unless additional mechanisms are controlling the eruption timing or restricting the longevity of the plumes. The addition of obliquity tides, and corresponding precession of the spin pole, can generate a number of model faults that are consistent with the pattern of plume detections. The locations and orientations of these hypothetical source fractures are robust across a broad range of precession rates and spin pole directions. Analysis of the stress variations across the fractures suggests that the plumes would be best observed earlier in the orbit (true anomaly ~120°). Our results indicate that Europa's plumes, if confirmed, differ in many respects from the Enceladean plumes and that either active fractures or volatile sources are rare.

1. Introduction

Europa's surface records a rich history of tectonic activity, including linked arcuate fractures called cycloids and straighter fractures called lineaments. Dilation, compression, and shear motions are also observed along many of these fractures, suggesting that fractures can be subjected to a variety of post-formation processes (for a review, see Kattenhorn and Hurford, 2009). Tectonic activity on Europa has been largely attributed to daily variations in tidal stress induced by Europa's eccentric orbit (e.g. Greenberg et al., 1998). Eccentricity causes Jupiter's location relative to Europa to change throughout each Europan day, leading to global-scale deformation and tidal stress. Lineaments and cycloids are both hypothesized to form mainly in response to tensile tidal stress, while strike-slip offsets have been linked to tidal shear stress (e.g. Greenberg et al., 1998; Rhoden et al., 2012).

Earth-based radar measurements show that Europa's obliquity (i.e. tilt of the spin pole) is also non-zero (Margot et al., 2013), likely forced by torques from Jupiter's other large moons (Bills et al., 2009; Baland et al., 2012). The maximum obliquity predicted by gravitational models is 0.1° (Bills et al., 2009; Baland et al., 2012), but the value depends sensitively on the interior structure assumed for Europa. For example, Bills et al. (2009) assumed that Europa is a homogeneous sphere. The models also predict that Europa's obliquity will change in magnitude periodically over 10–1000-year timescales. In addition, Europa's spin pole should

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precess at a rate of 0.3–3°/day (Bills et al., 2009). Obliquity and spin pole precession augment the stress field generated by eccentricity (e.g. Fig. 3 of Rhoden et al., 2010). The timescales for variation in the magnitude of the obliquity and the spin pole direction are short enough to be geologically-relevant.

Detailed analyses of tectonic features on Europa indicate that obliquity was a factor in their formation (Rhoden et al., 2010, 2012; Rhoden and Hurford, 2013), although they correspond to a somewhat higher obliquity than the gravitational models predict (between 0.2° and 1° depending on feature type). The tectonic record further supports the idea that several precession periods have occurred within the surface age and that there is a stronger signal of tidal stress change due to spin pole precession than non-synchronous rotation of the ice shell (Rhoden and Hurford, 2013). However, the absolute ages of tectonic features are unknown; interpretations of fractures are also compatible with a much slower precession rate than the gravitational models suggest.

Europa was clearly geologically active in the past, but whether it is still active today has remained a topic of much debate. However, recent observations, made with the Space Telescope Imaging Spectrograph (STIS) of the Hubble Space Telescope (HST), revealed H and O emissions near Europa's south pole that are best explained by two ~200-km high plumes of water vapor (Roth et al., 2014a). The plumes were identified in observations taken when Europa was near apocenter; no plumes were identified in two earlier observations when Europa was closer to pericenter. The apparent correlation with Europa's orbital position (i.e. true anomaly) was interpreted as possible evidence of a tidal origin for the plumes (Roth et al., 2014a). Similarly, active plumes emanating from fractures near the south pole of Saturn's moon, Enceladus (Porco et al., 2006; Spencer et al., 2006), have been shown to vary in intensity with its orbital position (Hedman et al., 2013) and have been linked to eccentricity tides (Hurford et al., 2007, 2012; Nimmo et al., 2007, 2014; Porco et al., 2014). However, tidal-control of Europa's putative plumes is still uncertain, especially after follow-up HST/STIS observations taken when Europa was once again near apocenter failed to yield a repeat detection (Roth et al., 2014b).

It is important to note that non-detections do not necessarily imply a change in H_2O plume abundance. Several effects contribute to detectability, such as the highly variable local plasma environment and the observing geometry (Roth et al., 2014b). However, to examine the potential role of tidal stress in controlling plume eruptions on Europa, we will begin with the assumption that non-detections indicate a lack of plumes.

The daily pattern of stress change on a fault due to Europa's eccentric orbit repeats exactly from one orbit to the next. Although the initial plume variability reported by Roth et al. (2014a) appeared consistent with eccentricity-driven tidal stress, the non-detection in January 2014 (Roth et al., 2014b) all but rules out an eccentricity-only model for controlling plume eruptions on Europa. An alternative explanation is that an additional mechanism acts to change the stress state on a fault even at the same true anomaly. Precession of Europa's tilted spin pole will cause the daily variation in tidal stress on a fault to slowly change over successive orbits. Because the five sets of HST/STIS observations obtained, to date, span a period of 14 years, the precession rates indicated by gravitational models would lead to a different spin pole direction in each of the observations.

We assess the conditions under which daily-varying tidal stress would be consistent with the plume detection pattern identified in the five available HST/STIS observations of Europa. Lessons learned from Enceladus are described in Section 2. Our tidal stress calculations, the stress conditions we assume for plume generation, and the different rotation states we consider are described in Section 3. Under these assumptions, we find that precession of Europa's slightly tilted spin pole can alter the stress state between observations, even when Europa is at a similar orbital position, such that tidal stresses are compatible with the pattern of plume detections and non-detections. The locations and orientations of the model faults that are most consistent with the observations, along with the inferred constraints on Europa's rotation state, are described in Section 4. Implications of our findings on the distribution of plume sources, future observations that can further refine (or refute) the tidal-control hypothesis, and comparisons with Enceladean plumes are discussed in Section 5.

2. Plumes on Enceladus

The *Cassini* spacecraft identified active and continuous venting of material emanating from the south pole of Enceladus (Waite et al., 2006; Hansen et al., 2006; Dougherty et al., 2006; Tokar et al., 2006; Porco et al., 2006; Spencer et al., 2006), which has now been shown to be the source of Saturn's E-ring (Kempf et al., 2010). The material forms a broad plume that has erupted material throughout the *Cassini* observations (>10 years) as well as in individual, intermittent jets (Spitale and Porco, 2007; Porco et al., 2014; Spitale et al., 2015). Continued observations using the *Cassini* VIMS instrument revealed that the intensity of the plume eruption varies with Enceladus' orbital position (Hedman et al., 2013). The main source of both the broad plume and the jets is a set of parallel fractures (Spitale and Porco, 2007), dubbed Tiger Stripes, which are also anomalously warm (Spencer et al., 2006; Spencer and Nimmo, 2013).

Like Europa, Enceladus maintains a mean motion resonance with neighboring Dione, which forces its eccentricity to 0.0047 (Peale, 1976). Hence, Enceladus experiences cyclic tidal stresses on the timescale of its 1.37-day orbit around Saturn. Tidal stress normal to the Tiger Stripes has been linked to plume eruptions, although the relationship between tides and individual jet activity may be more complex than the behavior of the broader plume (Hurford et al., 2007, 2012; Spitale and Porco, 2007; Porco et al., 2014). Tidal shear stress has been proposed to explain both heating and eruptions along the Tiger Stripes (Nimmo et al., 2007), but further analysis of plume activity suggests that the eruption timing is more consistent with normal stress (Porco et al., 2014). These interpretations suggest that the Tiger Stripe fractures mark the locations of conduits to a volatile reservoir that is opened and closed under the influence of tides.

Enceladus' shape and gravity field are most consistent with a regional sea near Enceladus' south pole, which sits beneath an ice shell 10s of km thick (Collins and Goodman, 2007; Iess et al., 2014). However, a global ocean that is considerably thicker/shallower at the south pole cannot be ruled out and may be more consistent with older fractures (Patthoff and Kattenhorn, 2011). In either case, the south polar sea is the most plausible source for the plume material, although the exact mechanism by which fractures interact with the liquid reservoir is unknown. The Tiger Stripe fractures may penetrate through the entire ice shell and tap the ocean directly, or there may be a more complex process of material transport that brings liquid water from the ocean to the shallow subsurface (see review by Spencer and Nimmo, 2013). Because tidal stresses reach a maximum of ~100 kPa, overburden stresses should dominate deeper than a few hundred meters and restrict opening of the Tiger Stripe fractures. However, hundreds of observations of plume activity at Enceladus demonstrate that a viable mechanism does exist for connecting fractures at the surface with liquid water beneath an ice shell 10s of km thick.

There is now evidence that both Enceladus and Europa have icy surfaces and subsurface reservoirs of liquid water, display