TEMPORAL BEHAVIOR OF THE ENCELADUS PLUME DURING THE CASSINI MISSION. C. C. Porco[1], F. Nimmo[2], C. Mitchell[3], M. S. Tiscareno[4] [1]Univ. of California, Berkeley, CA; cpcomments@ciclops.org; [2]Univ. of California, Santa Cruz, CA; [3]Boulder, CO; [4]SETI Institute, Mountain View, CA.

Introduction: In the opening months of the year 2005, a plume of µm-sized icy particles was found in Cassini Imaging Science Subsystem (ISS) images erupting from the south polar terrain (SPT) of the small Saturnian moon Enceladus [1]. Hurford et al. [2] predicted a diurnal variation in the plume's brightness with a peak 'near apoapse' based on the expectation of Europa-like cyclically varying tensional/compressional tidal stresses on a purely elastic ice shell.

Examinations of sparsely time-sampled ISS images of the plume spanning the first 6 years of the mission did in fact reveal a diurnal variation in plume brightness and, hence, mass. The main peak in the brightness was found in ISS images, and in data acquired by the Visual and Infrared Mapping Spectrometer (VIMS), to be ~200º in mean anomaly [3, 4]. Nimmo et al. [4] first compared the temporal behavior of the plume with a model of tidally-variable surface stresses, and proposed that the location of the peak reflected a phase lag in the response of the ice shell relative to the anticipated response for a purely elastic ice shell.

Since then, similar analyses on longer-baseline Cassini ISS data sets by two separate research groups revealed additional multi-year periodicities in the plume's brightness variation, ascribed to different causes by each group [5,6, and abstracts cited in both].

We present here, and extend, our work on this topic reported in our abstracts cited above. The amplitudes and phases of any long-term components in the plume's behavior, and how they compare to those of the diurnal component, have the potential to clarify the mechanisms, vent conditions, and perhaps the ice-shell properties responsible for the observed activity.

Methods: We investigated the variations in plume brightness as seen across the final set of ISS narrow-angle clear-filter plume observations spanning 12 years -- nearly the entire Cassini mission -- from 2006 to 2017. Figure 1 shows the results of the image reduction methods described in [4] and applied to all the images in our collection. The plume's brightness, or Integrated I/F, in km^2, derived at each orbital position, is plotted as a function of Enceladus' mean anomaly (MA). Immediately obvious is the variation over time in the amplitude of the main peak.

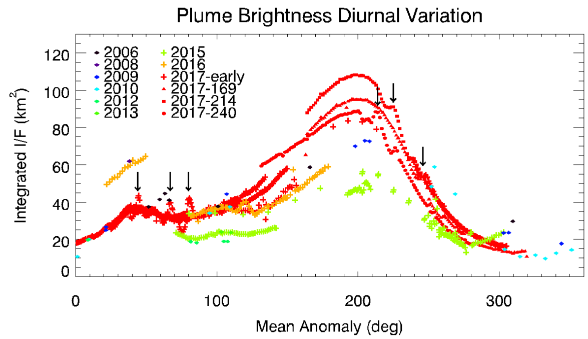

Fig. 1. Plume brightness or Integrated I/F (km^2) vs Enceladus' orbital position or Mean Anomaly from 2006-2017. Arrows point to features caused by an observational effect (see text).

A secondary peak near MA ≈ 50º, first noted by [7], was relatively large in the early- and mid-mission timeframes, and decreased dramatically in 2017. Abrupt and very noticeable changes in the brightness (noted in Fig. 1 by arrows) are an observational effect caused by the tendril featues -- the streamlines of icy particles escaping Enceladus and on the way to entering the E ring [8] -- interfering with the plume brightness measurements.

To search for long-period components in the brightness variations, we proceeded in three steps. We first found the best-fit diurnal variation, using a method similar to [4] but adopting the "normalized average stress" model of [9]. We then subtracted the best-fit diurnal model from the data, leaving a residual data set which exhibited long-period variations. Finally, we fit these remaining long-period variations with a simple sinusoidal model to obtain the best-fitting periods.

To verify that the extremely non-uniform temporal coverage in the Cassini ISS data set did not introduce spurious periodicities, we also analyzed synthetic libration data, sampled at the same times as the real data, as a check on our approach.

Results: In addition to the diurnal variation in plume brightness, we confirm and refine our earlier findings [5] for the characteristic parameters (periods and phases) of the strongest long-period variations at ~4 years, and ~11 years. These 2 periods are very close to periods associated with components of Enceladus' main 2:1 orbital resonance with Dione [10, 11].

At the diurnal period, while our earlier work on a more limited data set [4] reported a lag of ~60º, we now find a ~45º phase lag relative to a purely elastic response. The long-period response exhibits two main periodicities at ~4 and ~11 years, with the longer period having an amplitude, *b'*, ~50% larger than the shorter period (Table 1). Both the characteristic periods and the relative amplitudes of the long-period plume response are very similar to the characteristics of the forced long-period longitudinal librations of Enceladus: e.g, its 11-year libration amplitude is 58% larger than the 3.9 year amplitude [10].

Nominal period (yrs)	*b'* (km^2)	θ (º)	Δt (yrs)
4.0	13.3	179	1.99
11.0	18.6	126	3.85

Table 1: Fitted amplitudes (*b'*) and phase (θ) and time (Δt) lags are taken relative to observed Enceladus longitudinal librations sampled at the same times as the ISS data. In both cases, the data used are residuals with the diurnal component removed. For these experiments, the secondary plume peak has also been removed.

Conclusions: We conclude that it is long-period forced longitudinal librations of Enceladus, caused by the libration of the 2:1 orbital near-resonance and the circulation of an associated corotation-eccentricity resonance, both with Dione, that drive the long-period plume variability that we see. These components involve periodic variations in the mean motion of Enceladus, not in its eccentricity as suggested by [6].

We find that the diurnal brightness variations are only a factor of ~2 larger than the long-period brightness variations. This suggests that the amplitude of plume's tidal response at diurnal periods is very similar to that at periods of years. And the combined long-period brightness variation, as stated above, lags the forcing by a few years.

Any explanation for how Enceladus' long-period longitudinal librations drive plume brightness variations must satisfy these observational constraints. For instance, the large long-period phase lag rules out a viscoelastic response. Several possibilities likely satisfy the constraints: ice shell fracture healing and weakening, tidally-driven flow of water in the porous silicate interior, thermally-driven changes in water-filled fracture width and/or the librational response of the ocean.

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