The foreshock wave activity at lunar distances: Statistical study

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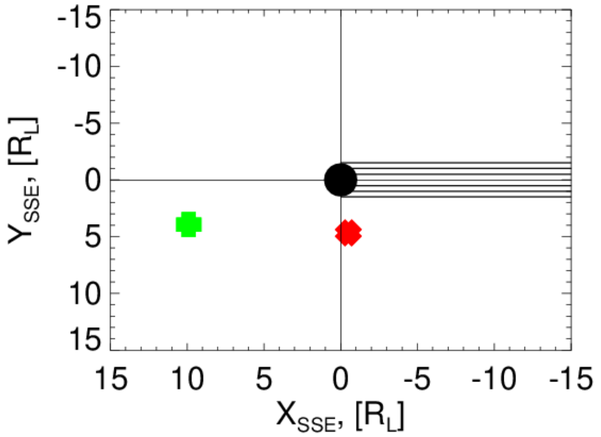
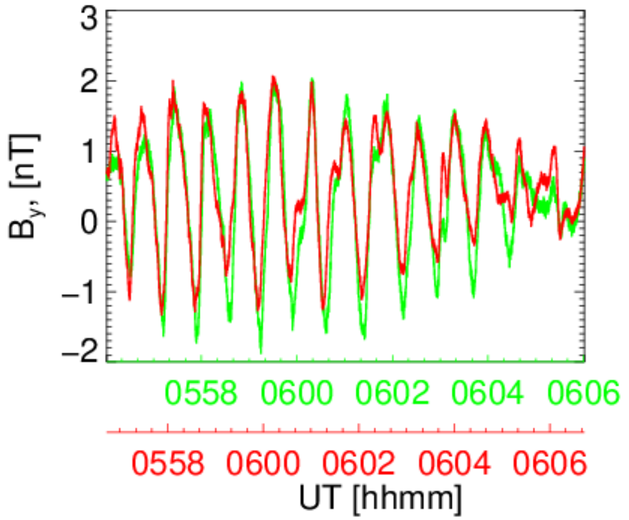
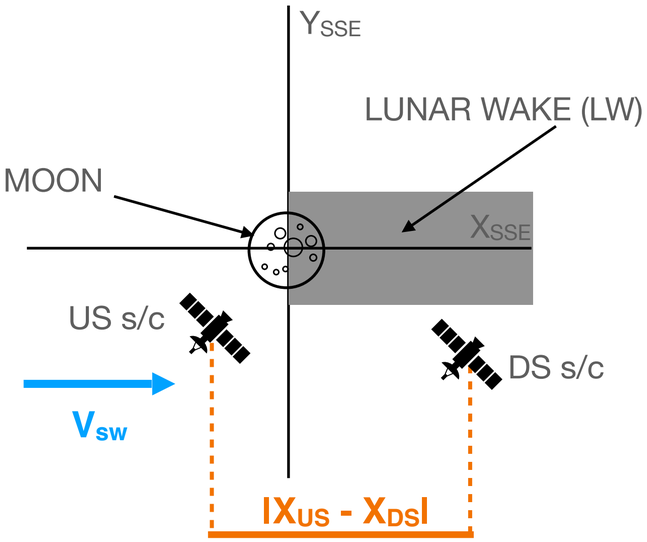
Data selection

1) ULF waves in the frequency range of 0.005-0.3 Hz;
2) two-point observation by THB and THC in 2012-2020;
3) ~10 minute intervals analyzed;
4) cone angle < 25 deg;
5) spacecraft (s/c) geometrically safely out of the lunar wake;
6) position of the Moon is in the upstream region ($X_{GSE} > 30\ R_E$);
7) time delay between s/c corresponds to time of solar wind propagation from upstream (US) to downstream (DS) s/c;
8) the foreshock is near the Moon:
   - presence of energetic ions reflected from the bow shock; this condition reduces our set from 6128 to 3709 intervals;
   - predicted θ_{Bn} angle < 45 deg at IMF intersection with the BS model [Jeřáb et al., 2005]; -7 $R_L < X_{BS} < 25 R_L$ (1188 data points);
   - a s/c separation is $X_{US} - X_{DS} > 5\ R_L$ (640 data points).



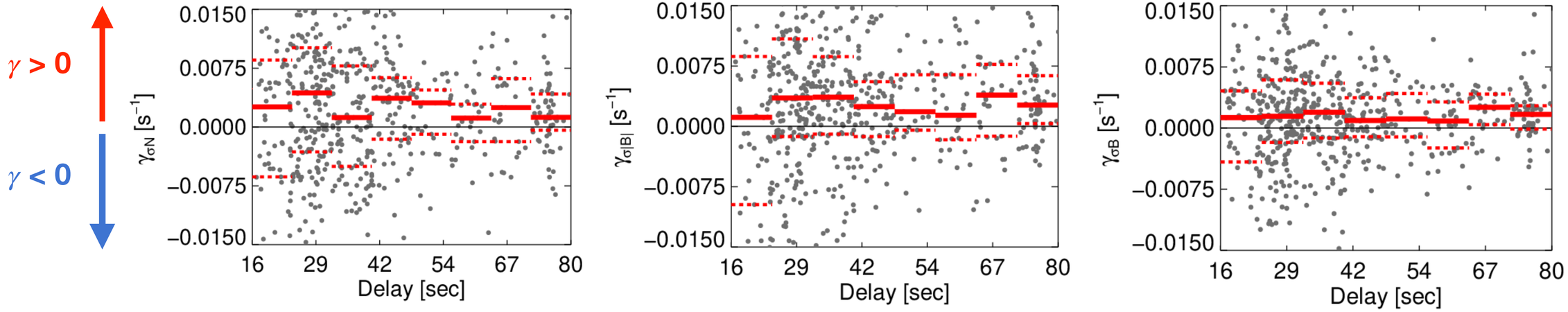




The time delay is estimated as: $\Delta t = |X_{US} - X_{DS}| / V_{SW}$

Statistics of fluctuations of plasma parameters and magnetic field

Growth rate of the density, magnetic field σ|B| and σB computed as a function of time delay between US and DS s/c along X_{SSE} axes.



We estimate the growth rate (γ) over selected 10-minute intervals using following definition:

$$\ln \frac{\sigma A_{DS}}{\sigma A_{US}} = \gamma \triangle t$$

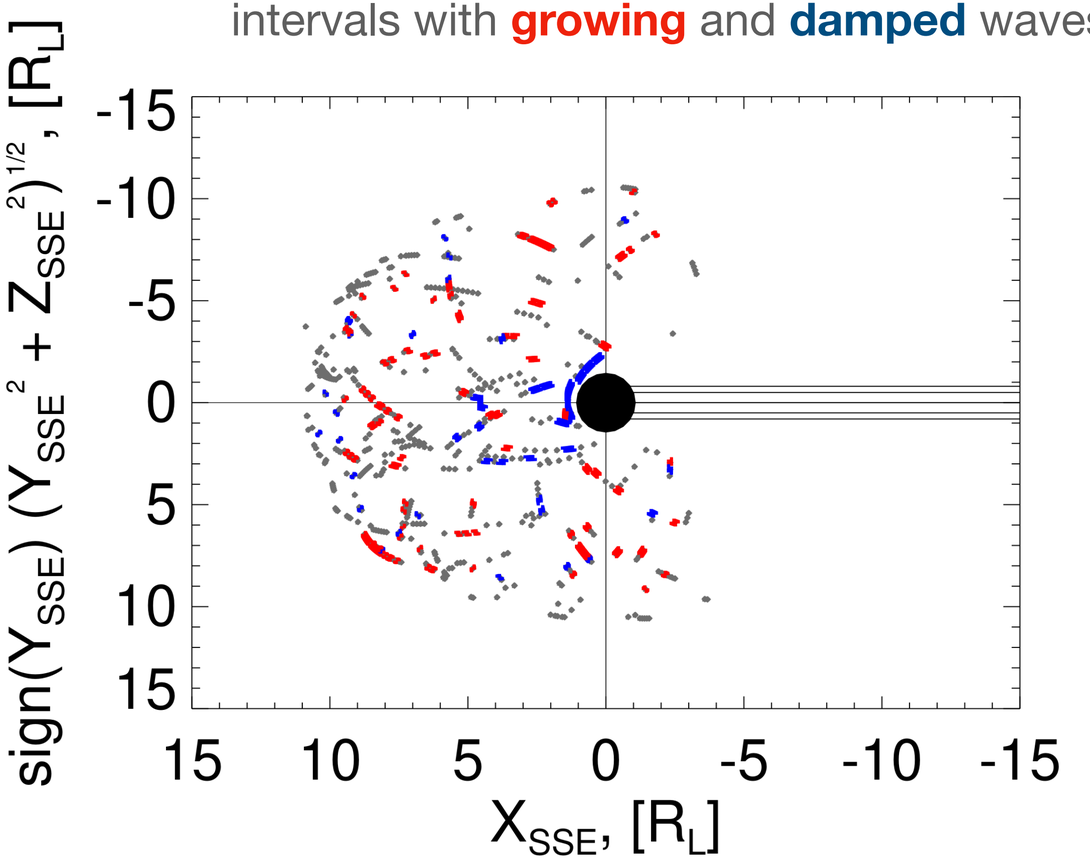
where σA_{DS} and σA_{US} are the standard deviations of variables observed by DS and US s/c, respectively.

The magnetic field, σB was quantified using the following equations: $\sigma B = \sqrt{\sigma B_x^2 + \sigma B_y^2 + \sigma B_z^2}$

The fluctuations of all parameters have a positive growing trend in average, but the set contains a large number of intervals that exhibit wave damping. Note the largest grow rate for N

ULF waves at the Moon

Projections of observed upstream s/c orbits onto the plane with respect to the Moon for intervals with **growing** and **damped** waves in SSE coordinate system.



Red color (γ) indicates intervals of positive growth rate.

Blue color (γ) indicates intervals of wave damping.

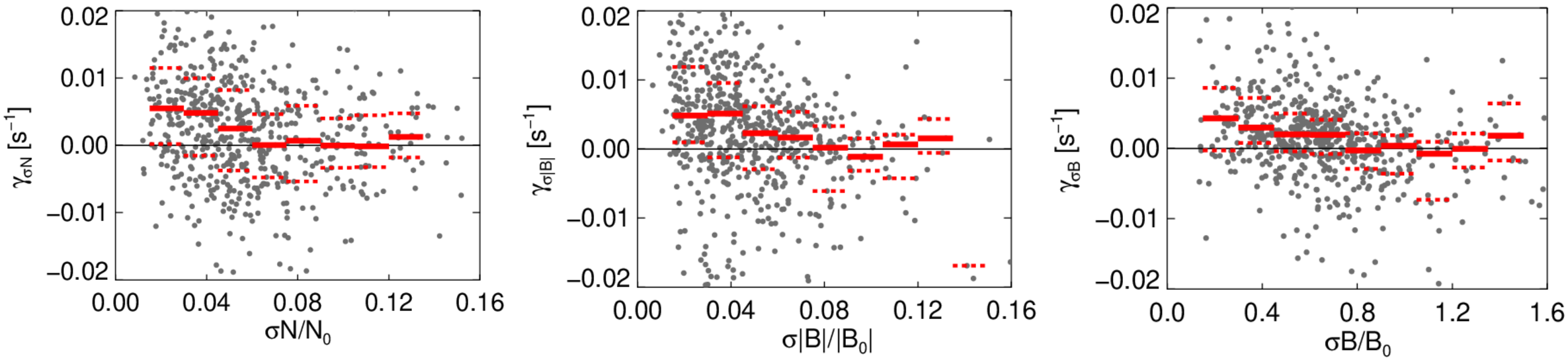
Grey color indicates intervals when waves neither grow nor damp.

The wave damping is dominant close to the Moon (< 5 R_L), while waves grow upstream the Moon

Discussion of the growth rate

We observe a large spread of particular events, thus we look for a reason!

The waves grow but the non-linear effects lead to a saturation of their growth rate and to excitation of new wave modes. However, new modes are growing at the expense of existing waves and the standard deviations do not increase accordingly. This scenario implies that the initial overall growth rate would be close to the upper limit of rates determined by our study and it would decrease with the fluctuation amplitude.



The growth rate is shown as a function of the normalized amplitude of fluctuations of each particular quantity.

Conclusion

- We presented a two-point statistical study of ULF waves/fluctuations observed on the orbit around the Moon in the distant foreshock during intervals of nearly radial IMF.
- The study reveals that fluctuations of all parameters (IMF magnitude, its components and ion density) are growing toward the bow shock in a statistical sense.
- Analysis demonstrates that the Moon and its surrounding affect the growth rate of ULF fluctuations significantly: close to the Moon ULF wave damping is dominant, while in upstream, the waves rather grow.
- Carefully selected conditions allowed us to demonstrate a reduction of the growth rate due to non-linear effects.

Thank You for attention!